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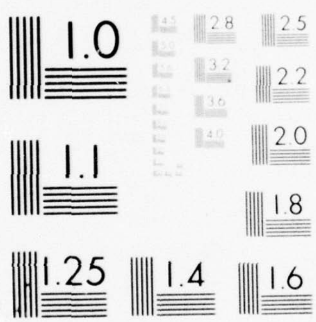

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THE JOHNS HOPKINS UNIVERSITY

Department of Mechanics and Materials Science

ULTRASONIC DETECTION OF FATIGUE DAMAGE IN AIRCRAFT COMPONENTS

(FIRST ANNUAL REPORT)

by

Robert E. Green, Jr.
Robert B. Pond, Sr.

Air Force Office of Scientific Research/NA
Contract No. F44620-76-C-0081
March 1977

Baltimore, Maryland 21218

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FATIGUE

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Ultrasonic Detection of Fatigue Damage in Aircraft Components

ANNUAL REPORT

(March 1, 1976 - February 28, 1977)

Air Force Office of Scientific Research

Contract No. F44620-76-C-0081

MARCH 1977

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Introduction

During the past several years, under the sponsorship of the Air Force Office of Scientific Research Contract No. F44620-71-C-0062, the current investigators have studied various methods of detecting the onset of fatigue damage in metals by use of ultrasonic techniques. A systematic comparison between body wave reflection, surface wave reflection, ultrasonic attenuation, and acoustic emission showed that body wave reflection and surface wave reflection techniques are inferior to ultrasonic attenuation and acoustic emission techniques for the early detection of fatigue damage. This is because both reflection techniques require that an appreciable fraction of the available ultrasonic energy be reflected from a crack of sufficient size and correct orientation in order to be detected. To the contrary, both ultrasonic attenuation and acoustic emission can detect movement of dislocations prior to micro-crack formation.

Both ultrasonic attenuation and acoustic emission techniques for the detection of fatigue damage employ fixed sensors and permit continuous remote monitoring. Acoustic emission can detect crack formation and movement which is not directly in the normal sound field of the sensor. Ultrasonic attenuation measurements can only detect defects created within the sound field of the transducer. Acoustic emission can only detect creation or growth of flaws in a material, while ultrasonic attenuation can detect static flaws as well as dynamic flaws. For this reason, acoustic emission must be monitored continuously in order not to miss any defect creation or motion. Intermittent

ultrasonic attenuation measurements permit detection of defect creation or rearrangement between measurements. Acoustic emission is capable of detecting dislocation breakaway from pinning points. Ultrasonic attenuation can detect vibration of dislocation loops between pinning points as well as breakaway. Acoustic emission flaw detection systems of current design normally operate in the frequency range from 20 kHz to 1 MHz and in this range background noise is intense. Filtering and special transducer arrangements coupled with logic circuits and computers have circumvented this problem in some cases, but the noise problem remains a major one. Ultrasonic attenuation systems normally operate in the frequency range above 1 MHz where background noise is usually negligible. The general waveform of an acoustic emission signal cannot be specified and is extremely difficult to separate from noise sources having the same frequency distribution since both occur in a near random fashion. The waveform of an ultrasonic pulse is easily determined and it is a simple matter to electrically separate the signal from noise in the ultrasonic attenuation technique even if the noise is of the same frequency since the ultrasonic signals occur at regular known intervals in time and noise signals arrive at irregular intervals.

Ultrasonic attenuation measurements made simultaneously with fatigue tests on aluminum specimens gave warning of crack initiation and eminent fracture much earlier than conventional ultrasonic methods. This was found to be true for metal bars which were initially defect free and for metal bars which initially contained induced latent defects. The remarkable success of the ultrasonic attenuation method of detecting

fatigue damage as developed in this program is clearly evident in the previous publications (1-5).

Although the ultrasonic attenuation technique is superior to the acoustic emission technique in many respects, one important advantage of the acoustic emission technique is the remote sensing capability it provides. Due to the potential offered by the acoustic emission technique in this regard, work was initiated to determine if acoustic emission could be successfully exploited as a fatigue monitoring technique. A detailed survey of the acoustic emission literature revealed that although several previous investigators had monitored acoustic emission during fatigue testing (6-18), considerable additional work was required before acoustic emission can be reliably used as a continuous monitor during fatigue cycling to predict crack formation and fracture. The main problem associated with fatigue failure prediction by acoustic emission monitoring is the difficulty of separating the acoustic emission signals associated with defect creation and movement from background noise. Since the amplitude, frequency content, and propagational characteristics associated with elastic waves emitted from various structural defects are unknown, it is evidently clear that acoustic emission monitoring will not be optimally suited for in-service fatigue damage detection until much more work is done to elucidate the basic causes of the emissions themselves as well as the particular features of the emissions directly attributable to the underlying defects.

The current practice for evaluating structural damage by acoustic emission monitoring is to count the signals emitted during deformation of the material and to plot the results as total counts or count rate as a

function of some measure of the deformation such as stress, strain, or the number of fatigue cycles. A number of problems are associated with this simplistic approach including a lack of knowledge of the influence of test specimen geometry on the received signals, of the effect of the medium coupling the acoustic emission transducer to the workpiece, and the amplitude and frequency response of the transducer itself. Moreover, the signals are normally passed through a filter, discriminator, and gate circuit wherein an incoming signal above a set threshold voltage will produce a shaped output signal which is fed into a count rate or count totalizer circuit. In order to make reliable assessment of such data, it is normally assumed that all events producing acoustic emissions of sufficient amplitude to be counted are equally damaging to the structure, that all damaging events will produce acoustic emissions of sufficient amplitude to be counted, and that each event will cause an acoustic emission which will be counted only once and not overlap with other signals. To make such assumptions is improper since there is more than one type of event which can generate acoustic emission, some of which are damaging and some not, and there is very little documentation in the literature which permits discrimination between different events by acoustic emission techniques. A given high amplitude acoustic emission signal may be produced by a single event which causes damage to the structure or by the simultaneous occurrence of a number of small events which cause no structural damage but whose net effect is to produce the large acoustic emission signal. A structurally damaging event may occur but the emissions associated with it may be too weak, propagate away from the detecting transducer, or be of the wrong frequency to be detected. A

single event may take place with several emissions of sufficient amplitude that the detector records several counts for one event or a single event may be such that the direct signal and multiply reflected signals arrive at the detecting transducer at different times thus resulting again in multiple counts from a single event.

Slip, twinning, crack initiation, crack growth, and fracture are all events which produce structural changes in various metals and alloys including aluminum, titanium, and steel which are of primary importance in aircraft construction. All of these events produce acoustic emissions, and quite probably different acoustic emissions, since they have been well documented to produce different structural alterations. Moreover, in many alloys subject to fatigue cycling, several of these deformation mechanisms occur simultaneously and hence several sources of acoustic emission are simultaneously active. Therefore, it is extremely difficult if not impossible to assess the state of structural damage during fatigue testing from acoustic emission data unless the specific emission characteristics associated with each deformation-emission mechanism is individually determined beforehand.

With this purpose in mind, a detailed study has been initiated to determine the characteristics associated with various deformation mechanisms in metal single crystals and polycrystalline aggregates. Experiments on twinning (19,20) showed that a correspondence exists between the duration of the acoustic emission signal and the volume of twinned material as determined by cinematographic observation of the generation and growth of twin bands. It was also found that the direction of the stress, tensile or compressive, induced in the body of

the crystal due to twinning can be determined from the polarity of the elastic wave emitted by the twin as detected by the transducer. This last result points out an important problem associated with acoustic emission testing not noted by prior investigators. Since elastic waves emitted by various defects can have different polarities depending on the type of internal stress which generates the waves, it is possible for signal cancellation to occur at the detecting transducer. Thus, if two relatively large sources of acoustic emission generate waves of opposite polarity which arrive at the detecting transducer simultaneously, the destructive superposition of these two signals would yield no net signal at the transducer, while the initiating events themselves could conceivably play an important role in destroying the structural integrity of the test piece. Admittedly, it is highly improbable that complete signal cancellation would occur in actual practice, but partial cancellation and signal modification due to mutual interference of simultaneously arriving acoustic emission signals is highly probable.

Acoustic emission measurements made on a series of lead-tin binary alloys of different compositions during constant-strain-rate tensile tests (20,21) showed that different alloy compositions possessed different microstructures which, in turn, caused different structure sensitive acoustic emission signals. Immediate reloading of a number of the test specimens which had been previously loaded and unloaded showed that although the acoustic emission activity was reduced on the second loading, emissions commenced at the beginning of reloading at load levels much lower than the maximum level reached on the first loading. These results

gave direct experimental evidence against the often quoted "Kaiser Effect." Moreover, this work showed that for the alloys tested, chemical composition, microstructure, thermal history, and amount of mechanical deformation all affect the observed acoustic emission to a marked degree.

The phenomena of fracture of fibers in composite materials, brittle fracture of ceramics, glass and other materials, and mechanical twin formation are usually sufficiently gross that simple macroscopic inspection reveals the acoustic emission sources and the amplitudes of the acoustic emission signals are sufficiently large so that the signals can easily be detected above normal background noise levels. However, in other important practical cases, such as plastic deformation by slip and microcrack formation during fatigue cycling of ductile materials, a more sophisticated technique is required in order to reveal the defect emitting the acoustic emission signals. Moreover, since the amplitudes of the acoustic emission signals are much lower than those associated with fracture and twinning, much greater amplification is required in order to detect the acoustic emission signals. This increase in amplification necessitates either a corresponding decrease in the background noise sources including those associated with the various components of the test system or a more sophisticated detection system which can distinguish the acoustic emission signals in spite of the poor signal to noise ratio.

Research Progress Summary

The purpose of the present research being conducted under AFOSR Contract No. F44620-76-C-0081, is to extend and apply the ultrasonic techniques developed under AFOSR Contract No. F44620-71-C-0062 to the detection of fatigue damage in test specimens which are made from materials and possess geometries typical of actual aircraft components.

It has been well documented in the technical literature that the two nondestructive testing techniques, acoustic emission and ultrasonic attenuation, are extremely sensitive to the microstructural alterations associated with the mechanical deformation of materials. Both techniques have been extensively exploited in basic research experiments concerned with obtaining information about the fundamental mechanisms causing plastic deformation, microcrack formation, crack growth, and fracture and in applied technical investigations concerned with detection of defects causing failure in structural materials. Theoretical treatments have also appeared in which the observed experimental results for both acoustic emission and ultrasonic attenuation are attributed to similar deformation mechanisms. Yet, despite the extensive investigation and similarity in description of these mechanisms, only one brief study has previously employed the two techniques simultaneously, and this was restricted to copper single crystals (22).

In order to compare the merits of acoustic emission monitoring with ultrasonic attenuation monitoring as indicators of microstructural alterations during mechanical deformation of structurally important materials, both acoustic emission and ultrasonic attenuation measurements

were made simultaneously during tensile elongation of test specimens made from 1100-H, 6061-T6, 2024-T3, and 7075-T651 aluminum alloys (23,24). A photograph showing the experimental apparatus used in making these measurements is shown in Fig. 1. A paper based on these tests is attached as Appendix A and a Master's Essay which presents the test method and results in more detail is attached as Appendix B. On all specimens tested, the acoustic emission activity occurred predominantly during the pre-yield region, while no perceptible change in ultrasonic attenuation was detected prior to yield. Following yield, ultrasonic attenuation increased in some tests and decreased in others. Superimposed on these gross changes were local perturbations which were more pronounced for the high yield strength alloys and which were very sensitive to alterations in heat treatment. The results of this work indicate that, for the aluminum alloys investigated, the deformation mechanisms causing acoustic emission activity and ultrasonic attenuation changes are different and, therefore, simultaneous monitoring by both techniques constitute a complimentary test method which yields more information about the deformation mechanisms than either technique alone.

In order to fully understand and thereby utilize the acoustic emission phenomenon an additional series of tests was performed on a series of 7075 aluminum alloys. Part of the motivation for selection of this particular alloy was due to previously published opinions of other investigators as to the origin of the observed acoustic emission signals.

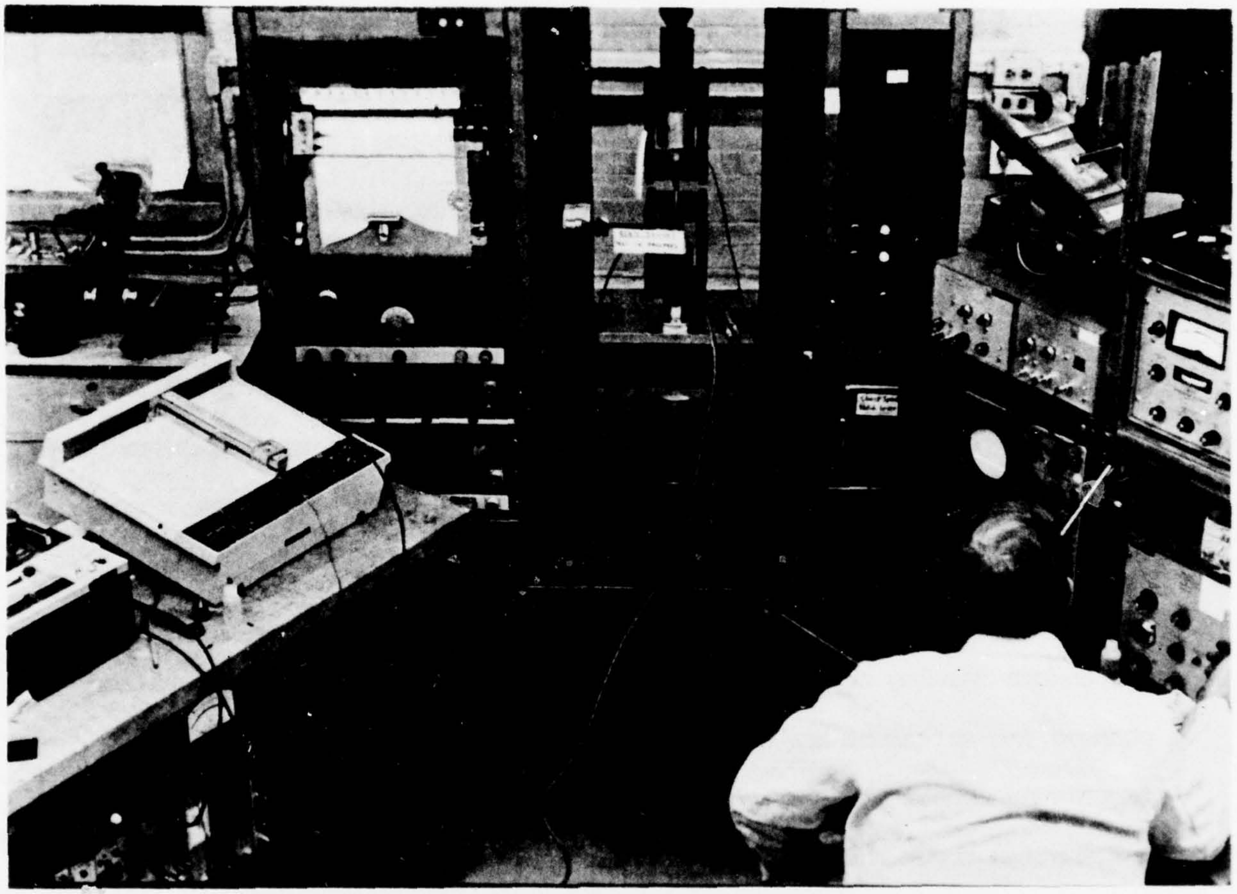

Figure 1. Experimental system for simultaneous measurements of acoustic emission and ultrasonic attenuation during tensile elongation of aluminum alloys.
Left: acoustic emission signal processing and recording
Center: tensile test and sensing transducers
Right: ultrasonic attenuation monitoring and recording

It should be noted that 7075, and all other age-hardening aluminum alloys, are found to contain three types of particles:

(1) Iron, copper, and silicon rich primary inclusions ranging in size from 0.1 to 10 μm in diameter.

(2) Chromium, manganese, or zinc rich intermediate particles ranging from 0.05 to 0.5 μm in diameter, deliberately added to control recrystallization and grain growth.

(3) Precipitate particles ranging from 0.01 to 0.5 μm in diameter, which strengthen the matrix.

Acoustic emission monitoring of the test specimens was conducted simultaneously with tensile deformation of the test specimens using the experimental arrangement shown in Fig. 2. An examination was made of the burst type of emission observed prior to macroscopic yield of 7075 aluminum alloys in the T6 heat-treated condition. The results of these experiments indicated that in keeping with the "Kaiser Effect" no acoustic emission activity was observed upon immediate reloading of the test specimen at load levels not in excess of those applied on the first loading. However, when the test specimen was allowed to sit at room temperature for three days between first loading and reloading, the burst type emissions were once again observed. This result appears to contradict any explanation which attributes the burst type emissions to particle cracking.

An additional series of tests were performed in which low level acoustic emission activity was monitored by recording the true

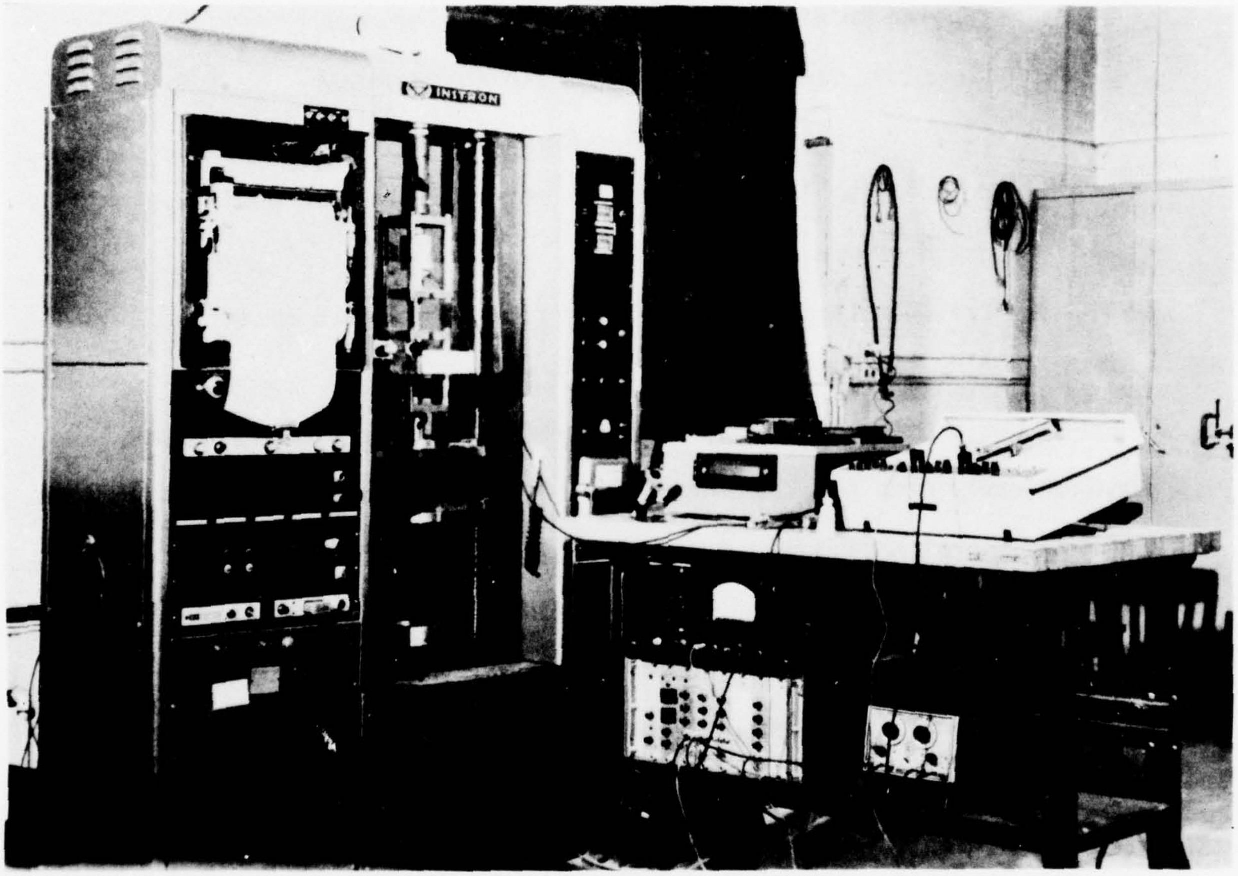

Figure 2. Experimental system for acoustic emission monitoring during tensile elongation of 7075 aluminum alloys.

root-mean-square voltage output from the detection system. As received material was found to behave in such a manner that this low level activity peaked in the region of 3 - 5% strain. A typical set of test results is shown in Fig. 3. Burst type emission is evident prior to and during yield with the low level emission reaching a maximum at 4.5% strain. Overall examination of the acoustic emission detected during the deformation of 7075 - T651 aluminum suggests the possible utilization of this type monitoring for detecting the onset of plastic deformation. This may be successfully accomplished by noting the sharp decrease in burst type emission and the gradual increase of low level activity.

In order to determine the role played by the precipitate particles in the acoustic emission activity, similar tests were performed on solution treated specimens. Marked differences were observed as shown by the results of a typical test depicted in Fig. 4. Whereas a small almost imperceptible peak in the low-level emission occurred near yield in the as-received material (Fig. 3), an extremely large sharp peak is observed at yield in the solution-treated samples (Fig. 4). In these latter specimens, little burst type emission is observed. A peak in the low-level emission is again observed at approximately 5 or 6% strain, but the maximum is not well defined. Additional elongation of the solution-treated samples led to a region of discontinuous yielding with corresponding fluctuations in the acoustic emission behavior.

Since extensive metallographic observation indicated essentially no difference between the microstructure of the as-received and

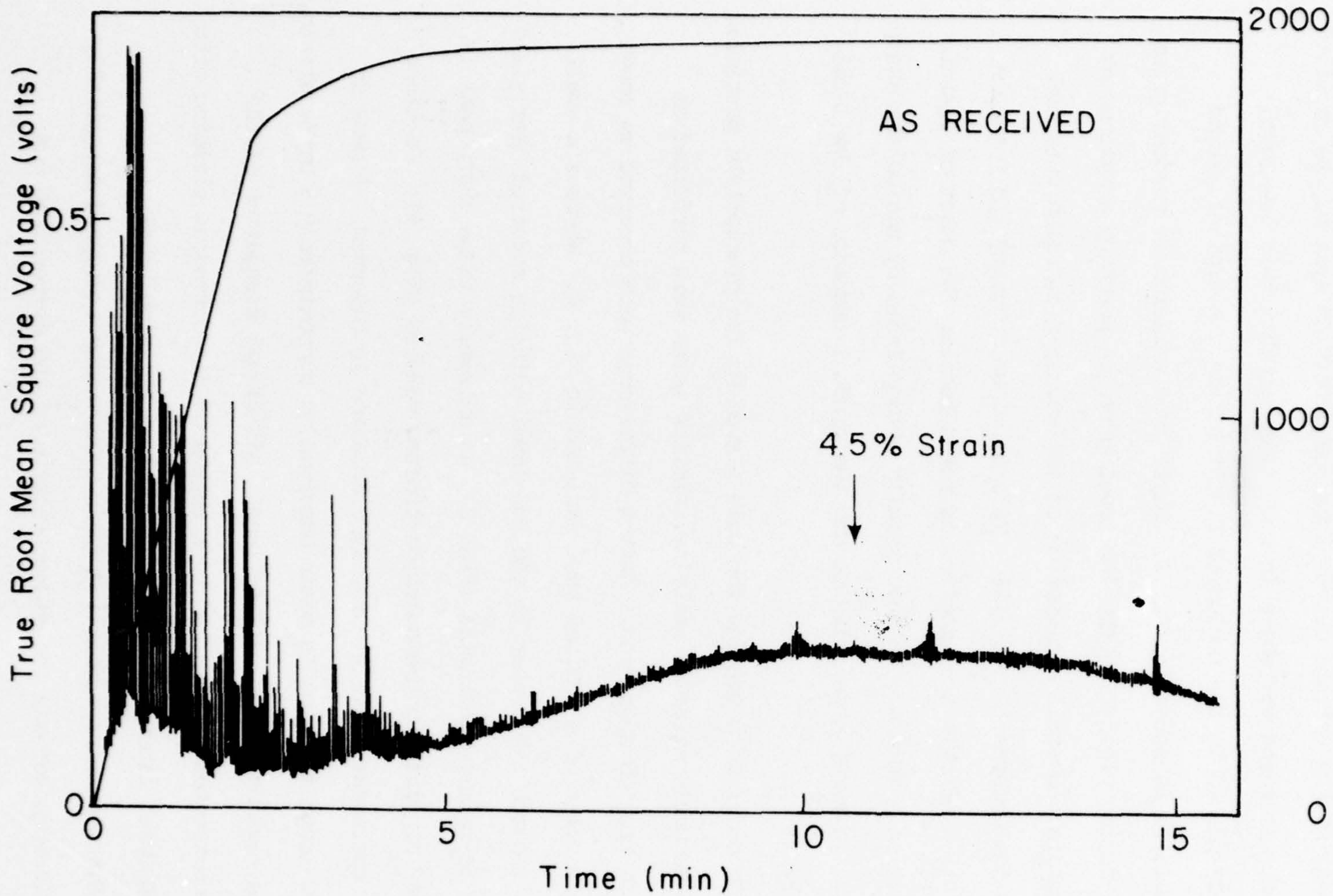

Figure 3. Typical results from recording of true root-mean-square voltage of acoustic emission from as-received 7075-T651 aluminum specimen pulled in tension at a constant elongation rate of 0.05 cm/min.

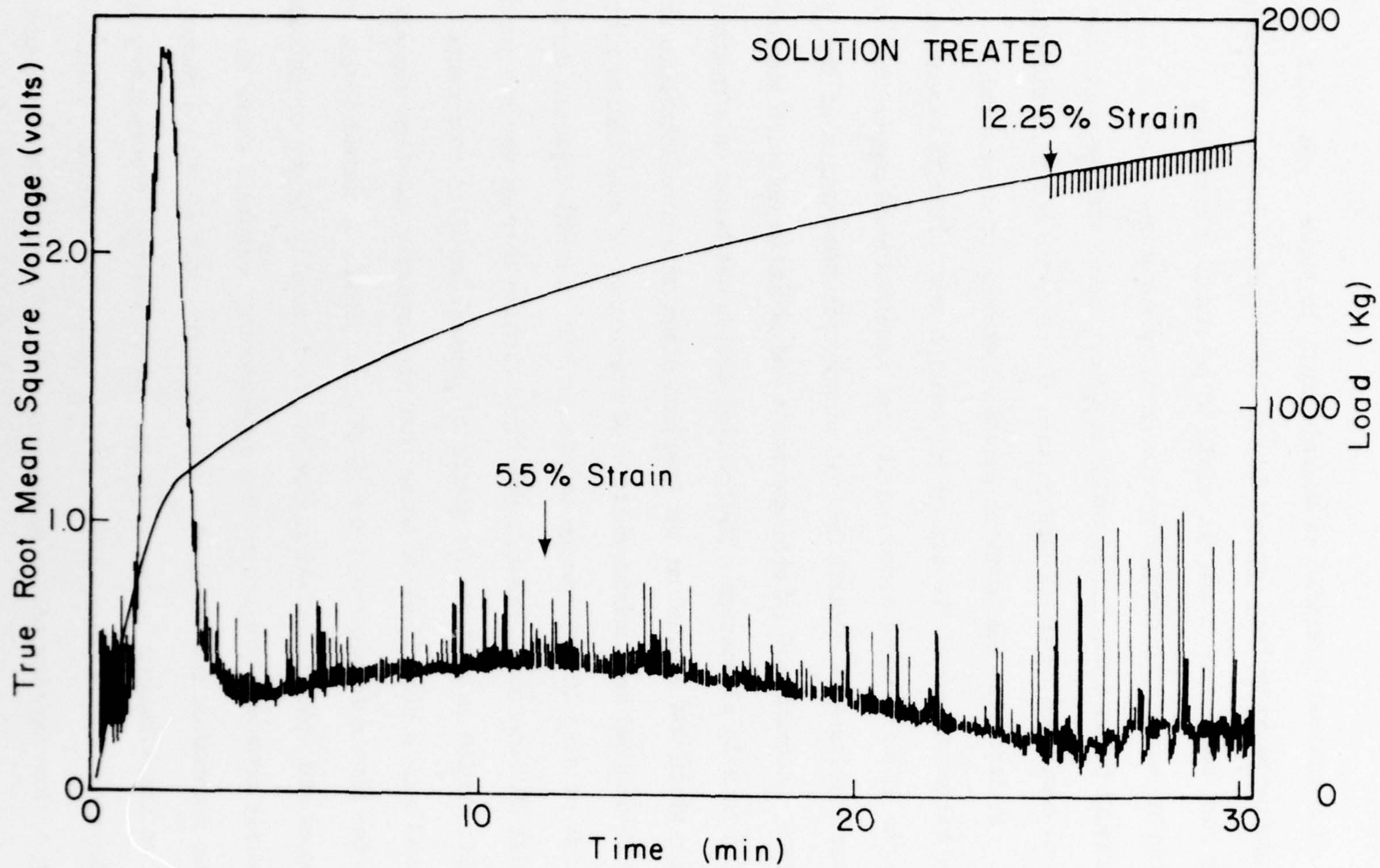

Figure 4. Typical results from recording of true root-mean-square voltage of acoustic emission from solution-treated 7075 aluminum specimen pulled in tension at a constant elongation rate of 0.05 cm/min.

solution-treated materials as regards particle types 1 and 2, if precipitates contribute appreciably to the observed acoustic emission they must be of type 3 and too small to be resolved optically. Electron microscopic and microprobe analyzer experiments are currently being conducted in order to detect these smaller particles and to correlate their appearance with the acoustic emission signals.

In assessing the acoustic emission behavior of a material detailed knowledge of the active deformation mechanisms is essential. Towards this end three microtensile test machines were constructed to permit simultaneous dynamic optical microscopic observation of the surface topography of tensile specimens and acoustic emission monitoring during tensile elongation. The initial design was based on a hydraulic device which was mounted on the specimen stage of a metallographic unit; this device had been successfully used previously to make motion picture records of slip line formation on the surface of metal crystals during tensile deformation. However, the fluid flowing through various portions of this device as well as the motion of several metallic components created such a high level of noise that the acoustic emission signals from the test specimen could not be discriminated. A second device was designed and constructed which used two mechanically driven crossheads to permit constant elongation rate experiments. Figure 5 shows this device mounted on the stage of a metallographic unit in such a manner that an instantaneous image of the surface of the test specimen may be displayed on a television monitor during tensile elongation. Figure 6 shows a close-up view of the mechanical drive microtensile test device.

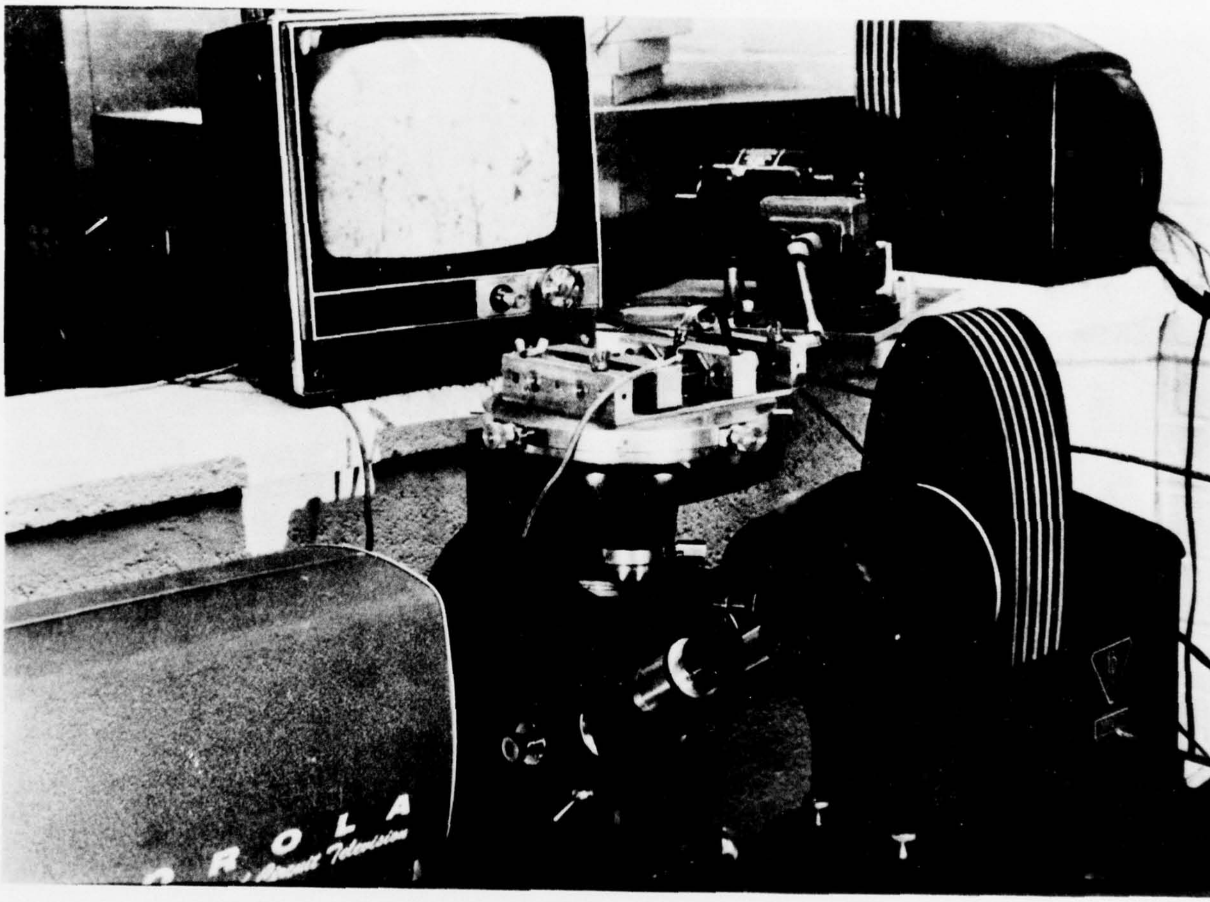

Figure 5. Variable speed mechanical screw drive microtensile test machine mounted on metallographic unit so that specimen surface can be viewed continuously on television monitor during tensile elongation.

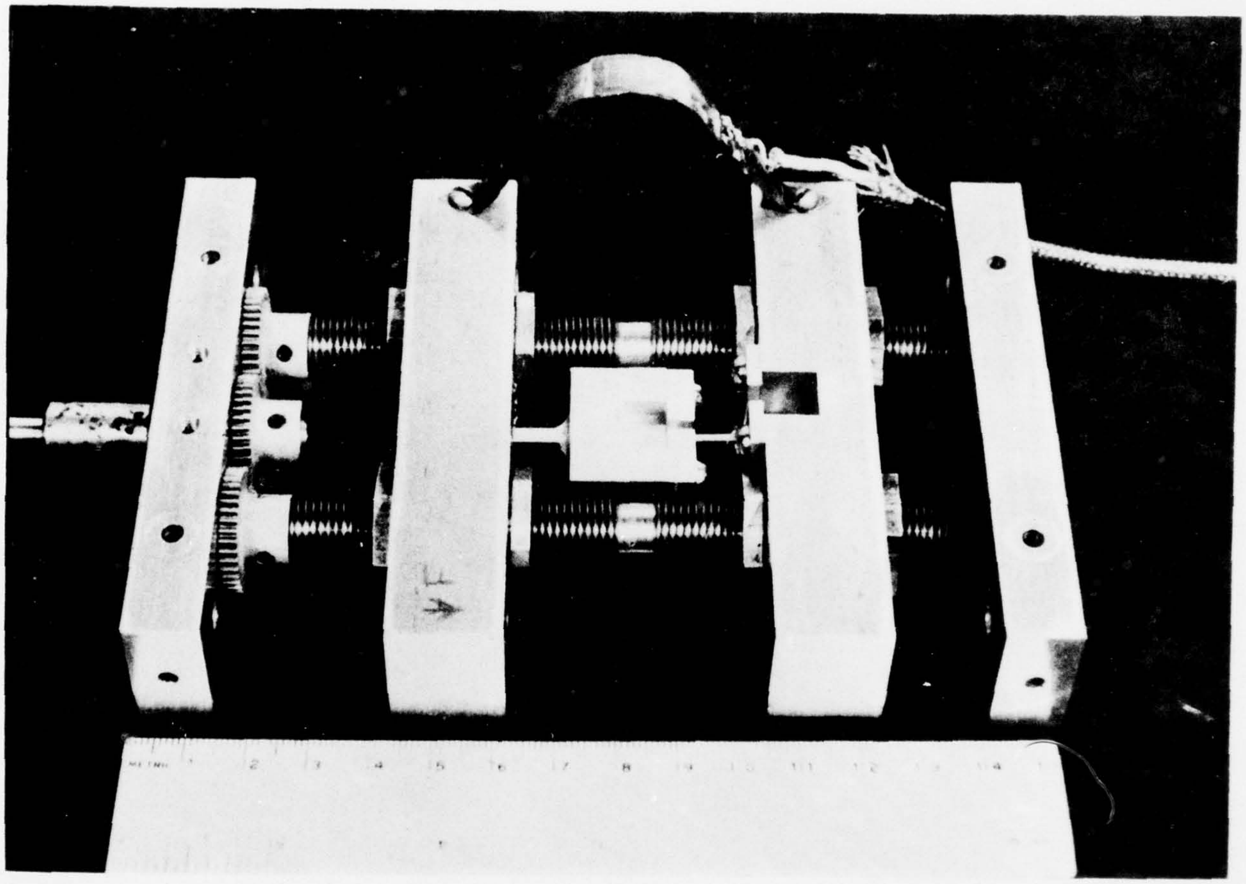

Figure 6. Close-up view of mechanical screw drive microtensile test machine.

In this instrument a variable speed electric motor-gear reduction drive combination, coupled to the tensile machine by two universal joints and a solid shaft, was used to turn a single gear which meshed with similar gears coupled to drive screws on either side. This configuration served to move the two crossheads equal amounts in opposite directions and thus maintained any desired portion of the test specimen in a fixed position with respect to the metallograph optical system. When this microtensile machine is mounted on the metallograph specimen stage, no force other than the weight of the microtensile tester is applied to the metallographic unit, and the tester is unaffected by the translational and focusing motions of the stage. This configuration permitted continuous monitoring of any area within the gage length of the test specimen by means of a closed circuit television camera mounted at the side viewing part of the metallographic unit. A video-type recorder was used to make permanent records of the entire deformation process. This instrument was used to study the strain rate dependent behavior of a lead-tin alloy deformed under normal and superplastic conditions. This particular material was selected because tin generates mechanical twins with associated large amplitude stress waves during deformation while lead deforms by slip processes which are very quiet. Since these alloys are soluble in each other for all compositions, tests on these materials can serve as a calibration of acoustic emission detection systems. Although the mechanical screw drive microtensile test machine was sufficiently quiet so that large amplitude stress wave emission associated with twin formation could be readily separated from

the background noise, a quieter device capable of superior isolation of the test specimen from the loading system was needed in order to satisfactorily detect the lower amplitude acoustic emission signals associated with slip processes.

A much quieter device was constructed in the form of the dead weight microtensile test machine depicted in Figs. 7 and 8. The base of this machine is fixed to a laboratory table. One of the specimen grips is fastened to the base while the other grip is attached to a moveable crosshead which slides on Teflon runners. A flexible cable fastened to the moveable crosshead passes through a hole in the machine base and over a pulley to a bucket into which water can be made to flow at a variety of rates. In addition to use of the Teflon runners, the transmission of acoustic energy from the loading system to the specimen was further reduced by isolation of the grip plates from the crosshead by Teflon washers. The surface deformation of the test specimen was observed with a traveling microscope mounted on a track and isolated from the testing machine by thick rubber mounts. Unlike the previous systems where the microtensile machines were mounted on a moveable microscope stage in order to permit focusing and specimen translation, these operations are performed by moving the microscope on its track for translational motion and on its rack and pinion mount for focusing. Two videotape recorders were used with this microtensile machine; one was used to record the television images as seen through the microscope, while the other was used to record the acoustic emission signals. The two

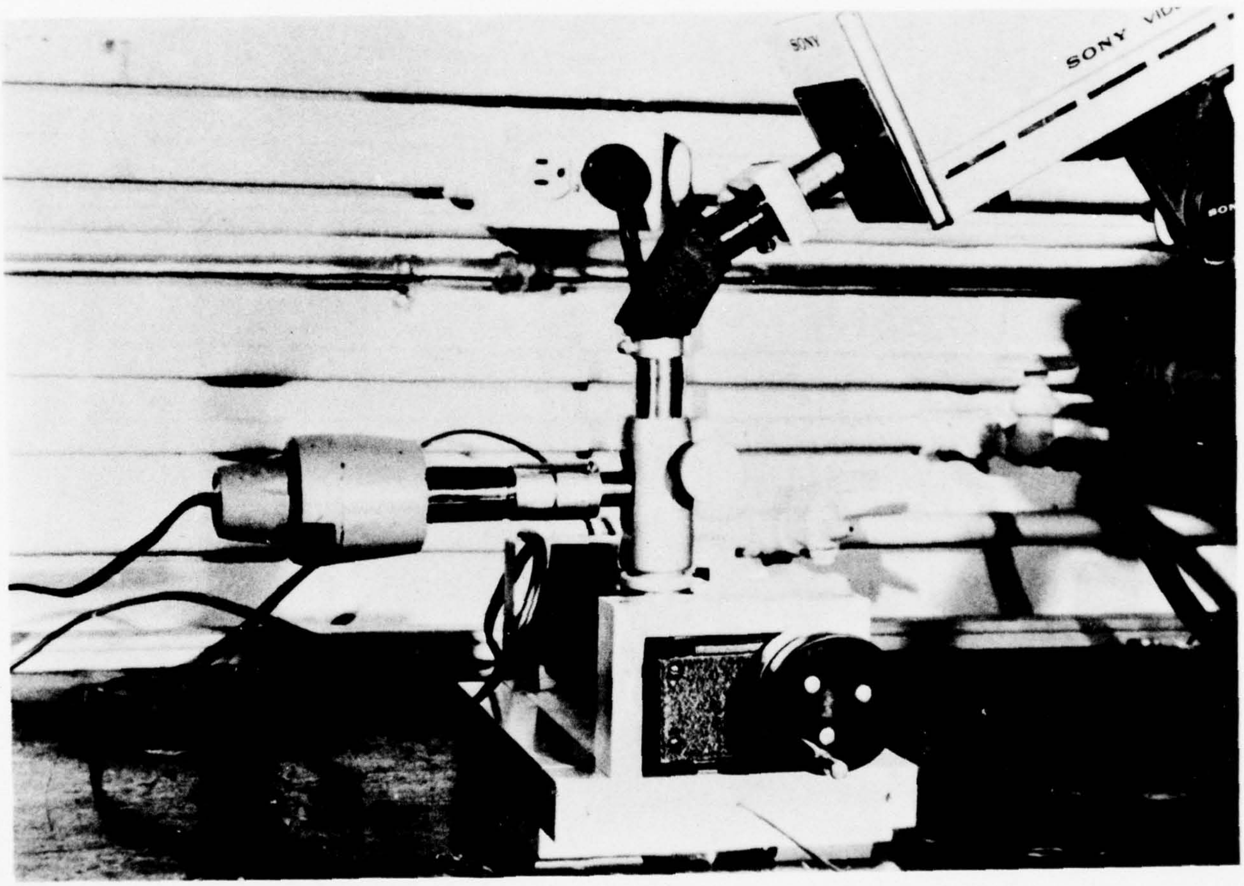

Figure 7. Dead weight microtensile test machine depicting traveling microscope and closed-circuit television camera.

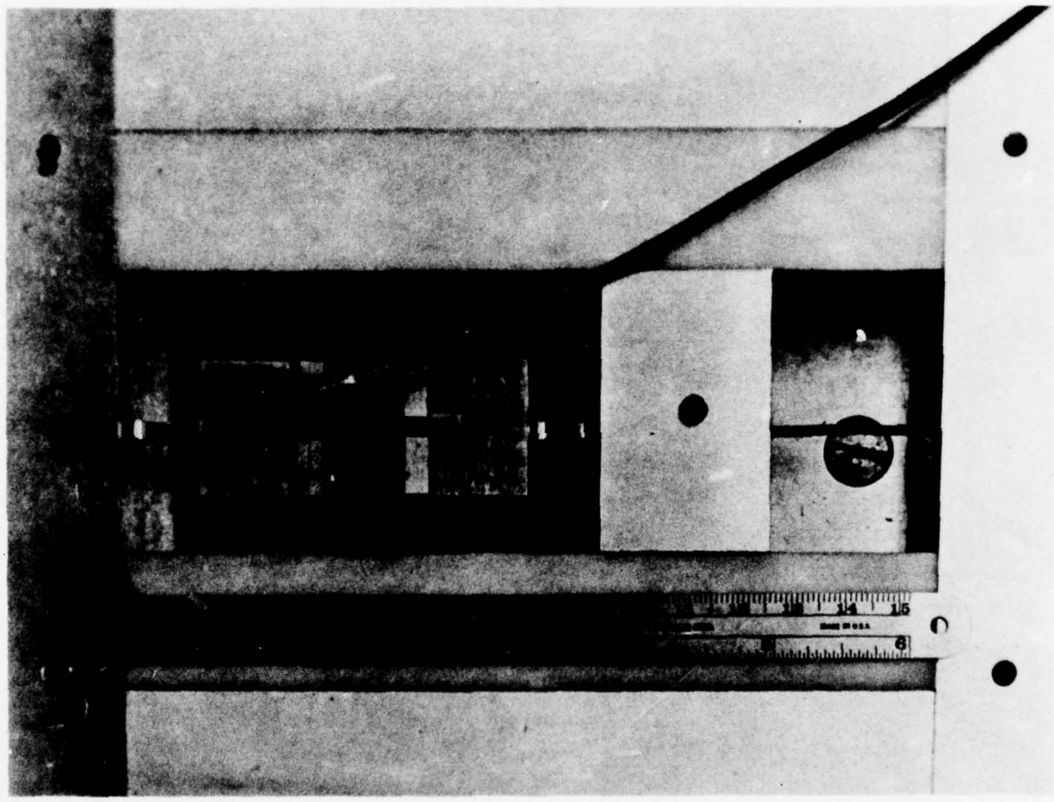

Figure 8. Top view of dead weight microtensile test machine with microscope and television camera removed showing test specimen and acoustic emission transducer.

videotapes were synchronized by putting a single signal into both audio channels. Preliminary results indicate that this loading system is relatively quiet in the frequency range of interest for acoustic emission testing, 50 kHz to 1 MHz, for a variety of specimen geometries and materials, tin, copper, 7075-T6 aluminum, and alpha-brass, as shown in Fig. 9.

In order to optimally distinguish between the acoustic emission signals generated by various structural defects and the signals caused by extraneous noise sources such as mechanical vibrations, rubbing, cavitation, and airbourne sounds, the acoustic emission signals must be characterized in detail. This characterization must include determination of the acoustic emission waveforms and frequency spectrum unmodified by the detecting transducer or by a video tape recorder. An acoustic emission characterization system which is optimally suited for this purpose has been designed and a proposal has been submitted to AFOSR in order to obtain sufficient funds for its purchase. The main component of this system is a transient recorder which will permit recording of the acoustic emission signals in real time in digital form and storage on magnetic tape. In turn, the magnetic tape record will serve as input to an existing PDP-11 computer for signal processing including fast Fourier transforms for spectral analysis. The same transient recorder will be used with an existing transducer calibration system in order to separate the transducer characteristics from the acoustic emission signals. Use of this system eliminates usage of the conventional video tape recorder which has limited bandwidth, clips negative signals more than positive

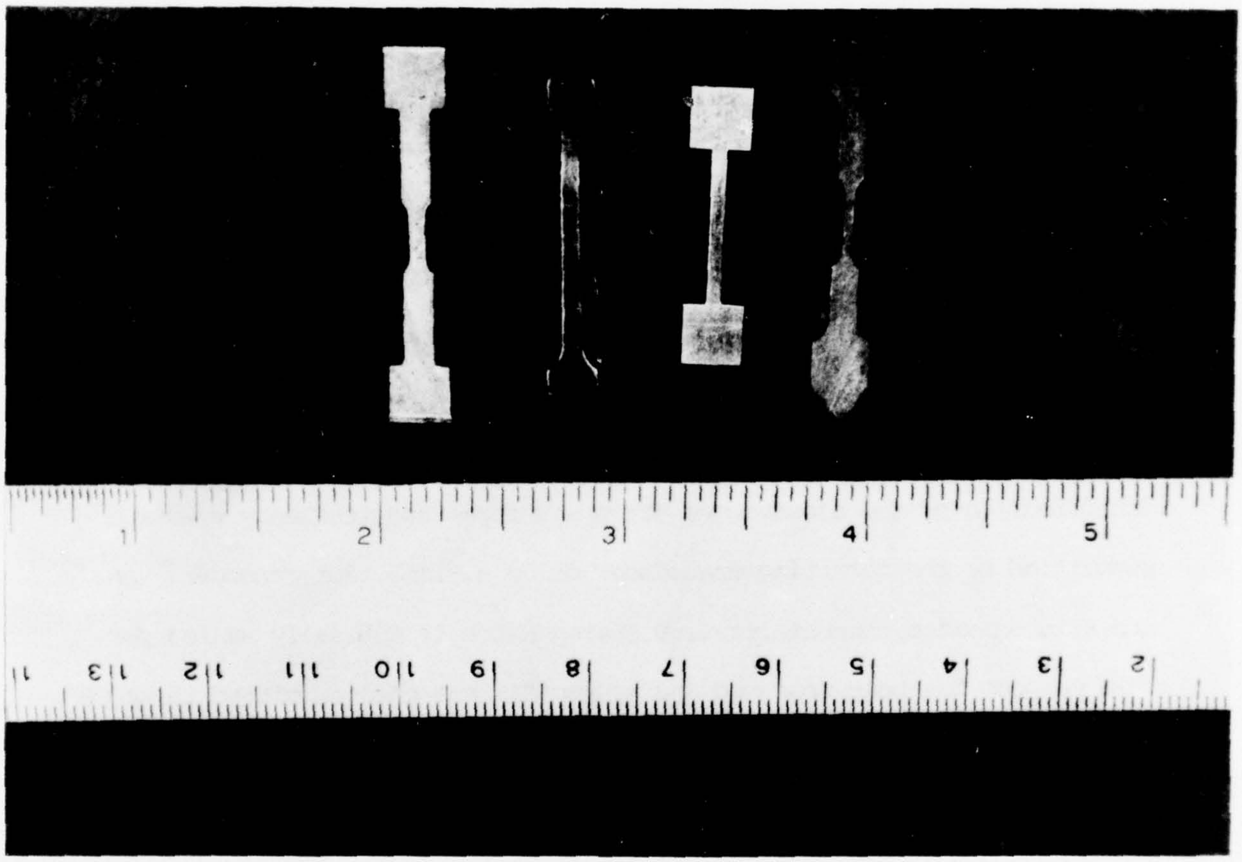

Figure 9. Specimens of tin, copper, 7075-T6 aluminum, and alpha-brass as used for microtensile tests.

ones, and requires use of a gate in order to remove signal artifacts due to internally generated synchronization pulses and alternation of the video recording heads.

In addition to the above acoustic emission work a paper has been written in which a detailed critical comparison has been made between theoretical treatments of the acoustic emission mechanisms and actual experimental observations (25). A summary of this paper which will be presented and published in full in the Proceedings of the Ultrasonics International 1977 Conference to be held in Brighton, England, in June 1977 is attached as Appendix C.

During the past year numerous attempts were made to conduct acoustic emission and ultrasonic attenuation measurements simultaneously during fatigue testing of specimens which were made from materials and possessed geometries typical of actual aircraft components. The purpose of these measurements is to determine the range of applicability of acoustic emission and ultrasonic attenuation monitoring to actual aircraft components. Due to the excessive background noise caused by the fatigue test machine, the acoustic emission monitoring has been temporarily suspended until the components necessary to construct the acoustic emission characterization system described above have been purchased and the system assembled and perfected. However, the ultrasonic attenuation measurements have continued. Figure 10 shows the experimental system used to make these measurements.

A large body of previous work (1-5, 23, 24) has shown that ultrasonic attenuation measurements provide a reliable indicator of

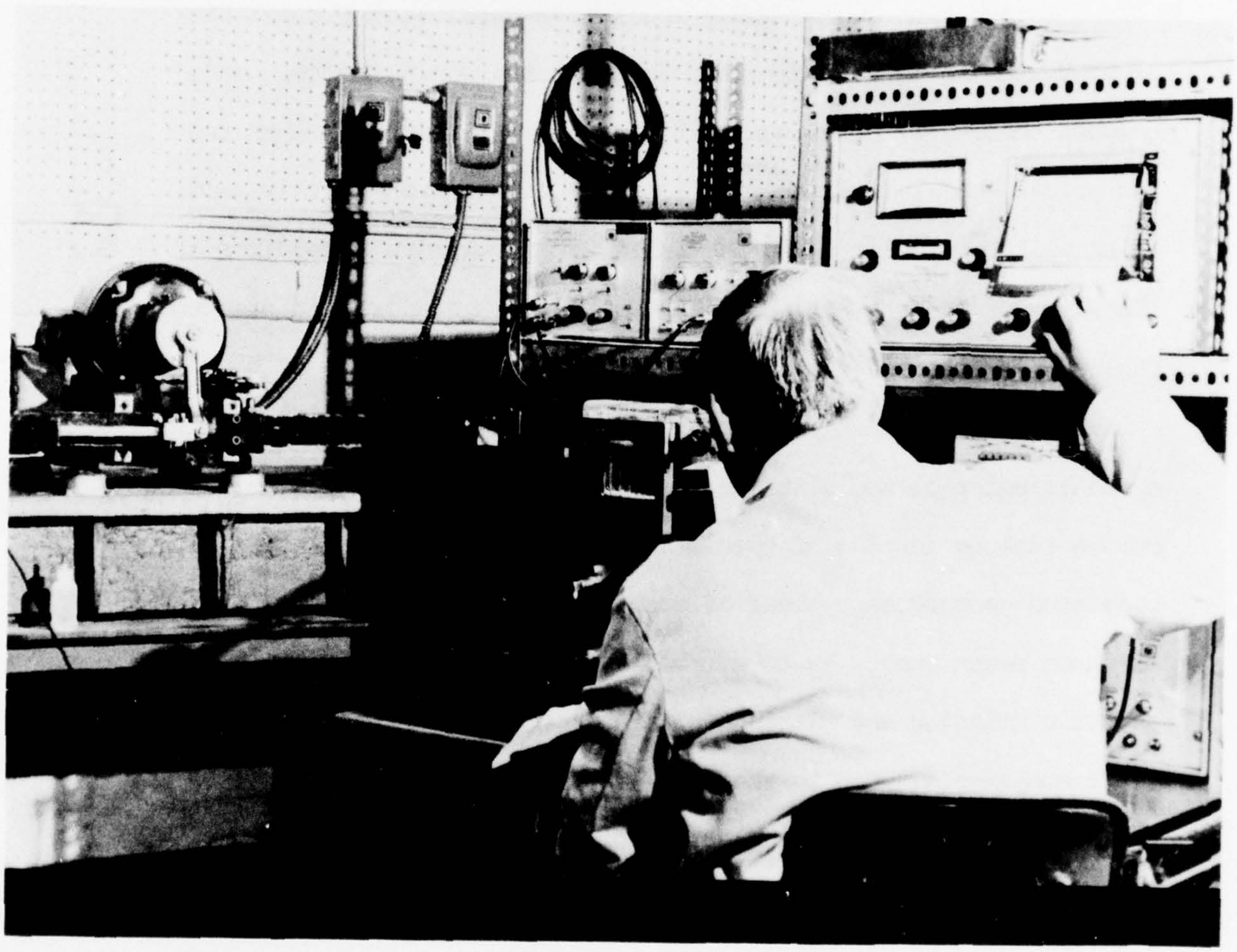

Figure 10. Experimental system for measurement of ultrasonic attenuation during fatigue testing of aluminum alloys.

early fatigue failure at approximately 60% of the specimens fatigue life. The major portion of the prior work was perfromed on test specimens in the form of rectangular bars 1 in. wide, 12 in. long, and 1/2 in. thick. Extension of these earlier measurements to test specimens which possess different geometries has been accomplished with good results. Many geometries have been ultrasonically investigated although only two series of fatigue tests have been run due to the necessity of constructing different grips for the fatigue machine for each geometry tested.

The first series of specimens tested were made from 7075-T6 aluminum alloy sheet 1/16 in. thick and were 1-5/8 in. wide by 16 in. long. Ultrasonic pulses were introduced into the specimens by means of an Aerotech Gamma Series Transducer with an active area 1/2 in. by 1 in. and a resonance frequency of 2.25 MHz. Initially this longitudinal wave transducer was coupled to an Aerotech 45° S mode conversion block, which permitted a shear wave to be introduced into the specimen at an angle of 45°. Difficulty was experienced using this conversion block in that the amplitude of the pulse reflected from the far end of the test specimen was so low that only one echo was received. Careful investigation and theoretical analysis revealed that the design of the mode conversion block was a major problem. The specimen contact area of the mode conversion block was much larger than necessary and this caused a decrease in the amplitude of the transmitted and received signals. The block was redesigned so that the contact area was reduced by approximately one half. This resulted in a marked increase in the amplitude of the transmitted pulse such that it was five times

that observed previously. A photograph of this redesigned mode conversion block with transducer attached and both in place on an aluminum alloy sheet of actual test configuration is shown in Fig. 11. The results from a typical fatigue test using this experimental technique is shown in Fig. 12, where the change in ultrasonic attenuation is plotted as a function of the logarithm of the number of fatigue cycles. Again the ultrasonic attenuation measurements gave early warning of fatigue failure much before conventional ultrasonic monitoring could detect an additional pulse reflected from a crack. These results represent the first reported use of this technique to give early warning of fatigue failure of metal sheets and a paper is being prepared to report these results in detail in a technical journal (26).

Currently, tests are being run on 7075-T6 aluminum alloy sheets 1/16 in. thick, 1-5/8 in. wide, and 16 in. long riveted in four places to a plate 1/4 in. by 1-1/4 in. by 3-1/4 in. as shown in the photograph of Fig. 13. Using the redesigned mode conversion block it is possible to monitor reflected pulses from the rivets as well as from the far end of the sheet specimen. As these experiments proceed successfully, it is planned to continue with additional specimen configurations which simulate as closely as possible actual aircraft components.

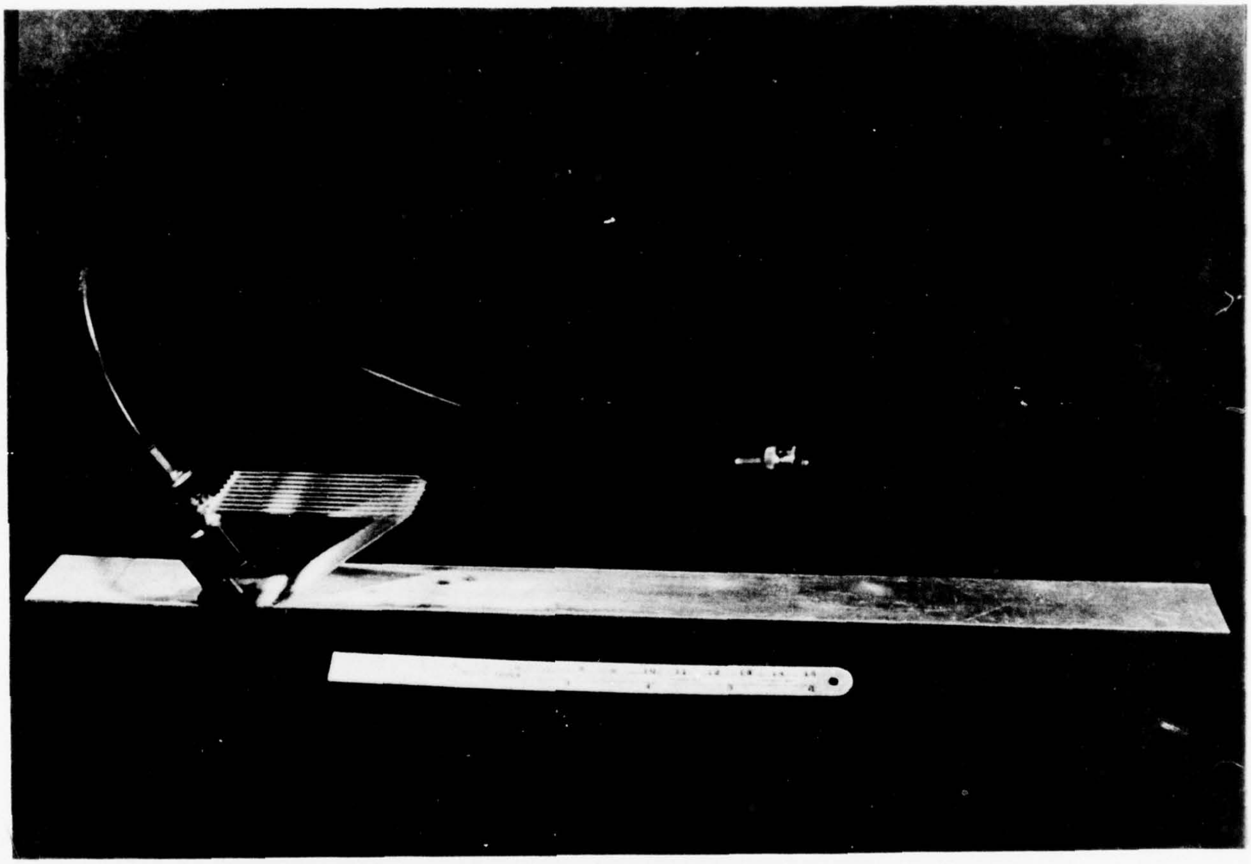

Figure 11. Redesigned more efficient mode conversion block with transducer attached in place on aluminum alloy sheet fatigue test specimen.

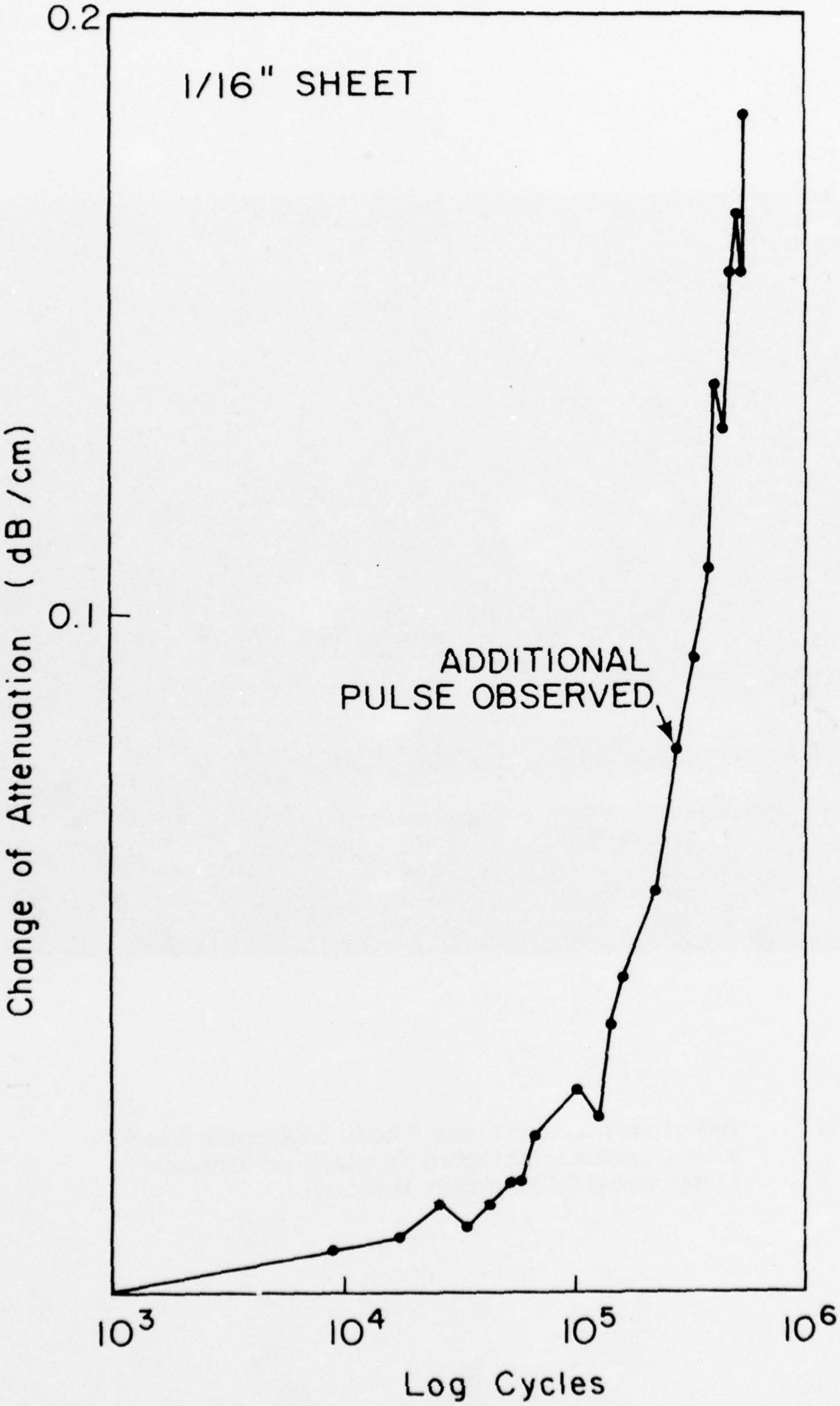

Figure 12. Change of ultrasonic attentuation as a function of the logarithm of the number of fatigue cycles for a 1/16 in. thick 7075-T6 aluminum alloy sheet.

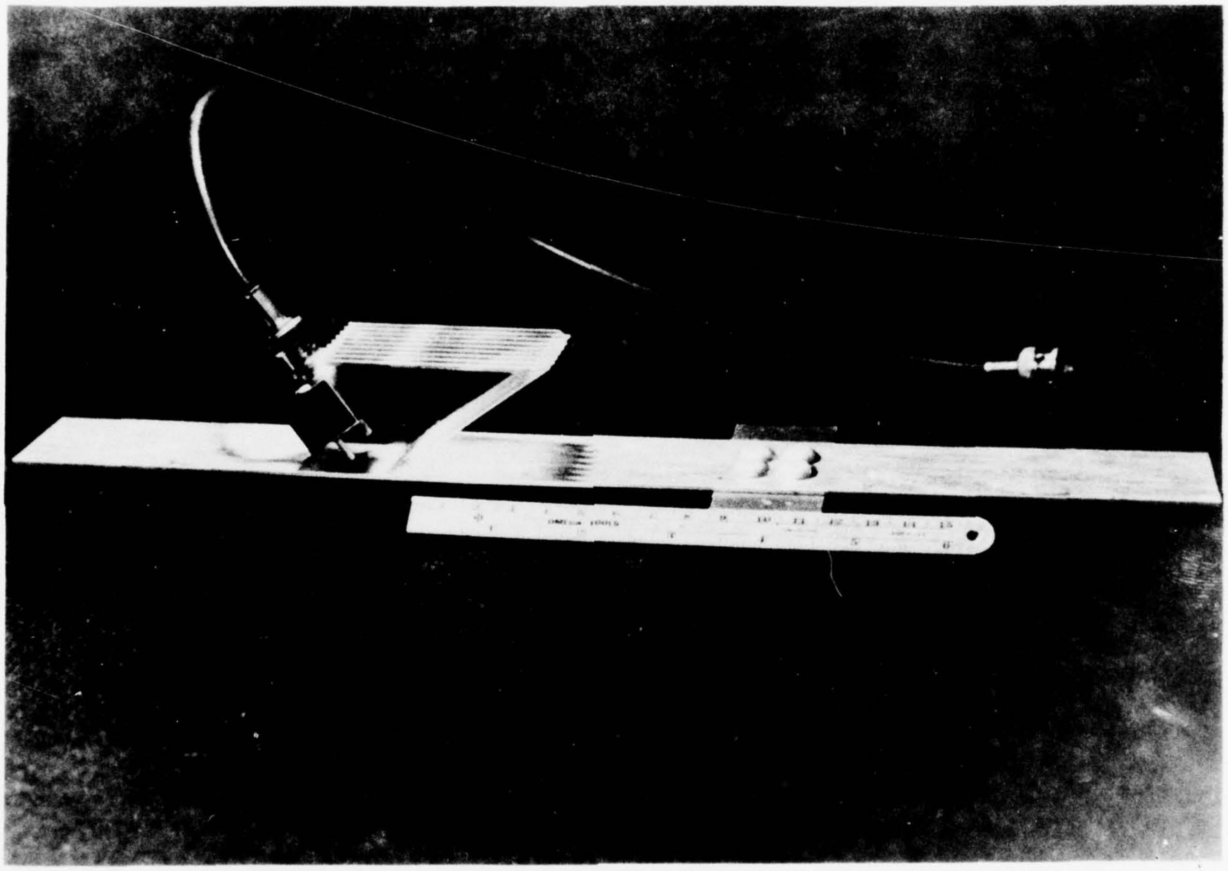

Figure 13. Experimental arrangement for testing an aluminum alloy sheet riveted to an aluminum plate.

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APPENDIX A

Published in the Proceedings of the Second International Conference on Mechanical Behavior of Materials, Boston, Massachusetts, p. 1646 (August 1976).

SIMULTANEOUS ACOUSTIC EMISSION AND ULTRASONIC
ATTENUATION MONITORING OF THE
MECHANICAL DEFORMATION OF ALUMINUM

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INTRODUCTION

It has been well documented in the scientific literature that the two non-destructive testing techniques, acoustic emission and ultrasonic attenuation, are extremely sensitive to the microstructural alterations associated with the mechanical deformation of materials. Both techniques have been extensively exploited in basic research experiments concerned with obtaining information about the fundamental mechanisms causing plastic deformation, microcrack formation, crack growth, and fracture and in applied technical investigations concerned with detection of defects causing failure in structural materials. Theoretical treatments have also appeared in which the observed experimental results for both acoustic emission and ultrasonic attenuation are attributed to similar deformation mechanisms. Yet, despite the extensive investigation and similarity in description of the fundamental mechanisms acting, only one brief study has previously employed the two techniques simultaneously (1). Effort has been devoted here to comparing the results obtained utilizing these two methods in light of earlier findings. Such a comparison yields more information about the mechanisms responsible for the mechanical deformation of metals than is obtained by either technique alone. In addition, previously unreported details of the behavior, evident from examining the information from the two techniques individually, are discussed (2).

The work has been limited to polycrystalline aggregates of aluminum alloys because of the technological importance of such face centered cubic materials and because these materials have played an important role in previous investigations

where either ultrasonic attenuation or acoustic emission monitoring was used.

EXPERIMENTAL PROCEDURE

One inch diameter rod stock of various aluminum alloys (1100 H, 6061 T6, 2024 T3, 7075 T651) was machined to have a reduced gauge section in a "dog bone" configuration. Gauge sections of 5.08 and 16.16 cm in length and diameters 1.27 and 1.02 cm were used. The end faces were machined flat and parallel. In general, the specimens were given no further preparation since the examination of commercial products was the primary interest.

All of the specimens were subjected to uniaxial tensile loading by an Instron testing machine. In these studies crosshead rates of 0.05 and 0.02 cm/min were used. In order to couple the grips to the load cell different couplers were employed to assure that no flexure of the specimen occurred during deformation, since this would cause spurious ultrasonics results. The grips, Fig. 1, which were specifically designed for this study, provided easy access to either end of the specimen for transducer placement, uniform uniaxial application of the load, and reasonable acoustic isolation from the loading machine. No influence of the mechanical or electrical operation of the Instron on either the ultrasonic attenuation or acoustic emission monitoring was encountered.

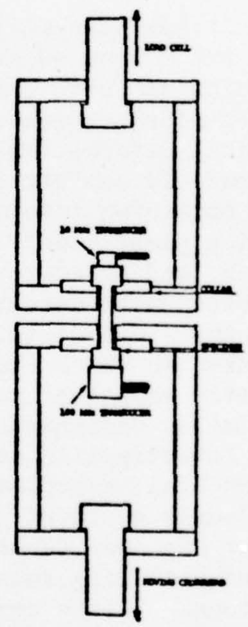

Fig. 1. Grip Configuration

Continuous ultrasonic attenuation measurements were made using a Matec Model 6600 Pulse Modulator and Receiver coupled with a Matec Model 2407A Attenuation Recorder. By subtracting the initial attenuation value and dividing by the instantaneous specimen length, the change in attenuation per unit length (dB/cm) was obtained. In conjunction with this monitoring

system a 0.5 in (1.27 cm) diameter Aerotech 10 MHz Gamma transducer was operated in the pulse-echo mode at a repetition rate of 200 per second. The transducer was directly coupled to the upper specimen face with nonaqueous stopcock grease. A 3 Kg weight was used to supply a constant load to the transducer, while a specially designed spacing ring was used to assure central positioning, avoiding excessive reflections of the pulse from the lateral surfaces. Care was taken to insure that the amplitude of the ultrasonic driving pulse was well below that necessary to excite the acoustic emission sensor. The acoustic emission system used in the present study consisted of a one inch diameter 100 kHz Panametrics Model 5070 resonant sensor coupled directly to the lower end of the specimen with nonaqueous stopcock grease and held in place by a spring. The signal from the transducer was amplified and band pass filtered from 10 kHz to 300 kHz by a Tektronix 1A7A High Gain Amplifier. Further filtering by a Kronhite Model 3202 Filter from 80 kHz to 120 kHz occurred before the signal was counted by a Monsanto Model 112A Counter. In these studies threshold counting and rate counting were both employed in order to best discern the acoustic emission behavior.

RESULTS AND DISCUSSION

Load, ultrasonic attenuation, and acoustic emission were monitored as a function of extension for the four aluminum alloys. A typical graph of the experimental results is shown in Fig. 2. For all alloys tested it was found that the acoustic emissions occurred predominantly during the pre-yield region of the deformation. In fact, in most cases, almost no acoustic emission was detected after yield. The ultrasonic attenuation, however, was found to exhibit an opposite behaviour, in that the change in attenuation per unit length prior to yield was essentially imperceptible. Upon yielding the change in attenuation increased in some tests and decreased in others. In addition, a local perturbation in attenuation change as a function of elongation was observed, which was most predominant in the alloys with high yield strengths, 2024 T3 and 7075 T651. In order to study these perturbations more fully, and to discern whether or not there was any corresponding activity associated with the acoustic emission a series of tests was performed on 7075 T651 specimens. During these tests a major part of the effort was devoted to making certain that the perturbations were only the result of the mechanical deformation of the test material

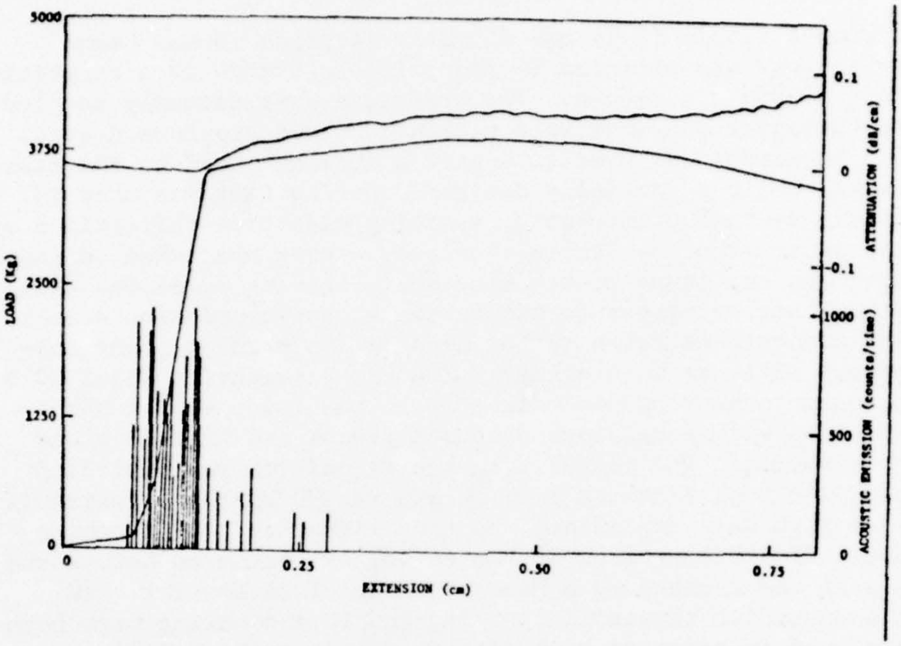

Fig. 2. Typical Plot: 6061 T6 Al. Crosshead Speed = 0.05 cm/min, Accumulated Acoustic Emission Counts for 15 sec Intervals Monitored at 80 dB Gain

and not some artifact introduced by the testing system. In this series of tests the specimen size and heat treatment were varied as well as the gripping arrangement and elongation rate. In every test the local perturbations were observed, with the most significant changes in behaviour occurring in those specimens which had been heat treated. Two particularly significant findings arose out of this series of experiments. First, during the testing of a specimen which had received a T6 heat treatment at a gain increased to 85 dB lower level emissions, of about the same amplitude level as that associated with the background, were detected. The rate of emission exhibited a maximum around 3% strain, although the previously pronounced emissions observed before yield were indistinguishable from the other emissions at this gain setting. The second significant finding was observed with another 7075 T651 specimen which was subjected to repeated loading and unloading to 393MPa; emission was again monitored at 80 dB gain. During the first loading the characteristic pre-yield emission occurred but on immediate reloading and upon reloading after 72 hours no emission was observed. However, on loading after allowing

the specimen to recover for 80 hours at 130°F, acoustic emission activity similar to that observed during the first loading was observed.

CONCLUSIONS

During tensile elongation of 1100H, 6061 T6, 2024 T3, and 7075 T651 aluminum alloys, the acoustic emission activity occurred predominantly during the pre-yield region. On the other hand, no perceptible change in ultrasonic attenuation was detected prior to yield. Following yield, ultrasonic attenuation increased in some tests and decreased in others. Superimposed on these gross changes were local perturbations which were more pronounced for the high yield strength alloys and which were very sensitive to alterations in heat treatment. The results of the present work indicate that for the aluminum alloys investigated the deformation mechanisms causing acoustic emission activity and ultrasonic attenuation changes are different and, therefore, simultaneous monitoring by both techniques constitute a complimentary test method which yields more information about the deformation mechanisms than either technique alone.

ACKNOWLEDGEMENTS

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APPENDIX B

SIMULTANEOUS ACOUSTIC EMISSION AND ULTRASONIC ATTENUATION MONITORING OF THE MECHANICAL DEFORMATION OF ALUMINUM

by

John Christian Duke, Jr.

An essay submitted to The Johns Hopkins University
in conformity with the requirements for the
degree of Master of Science in Engineering

Baltimore, Maryland

The Johns Hopkins University

1976

ABSTRACT

Ultrasonic attenuation and acoustic emission monitoring have been shown to be extremely sensitive to the mechanical deformation of metals. Theoretical treatments have also appeared in which both phenomena are attributed to similar deformation mechanisms.

Results are reported here of tests in which ultrasonic attenuation and acoustic emissions have been monitored simultaneously during tensile deformation of several aluminum alloys, 1100H, 6061 T6, 2024 T3, 7075 T651. The results obtained are compared, in light of earlier findings, in order to further elucidate the fundamental mechanisms involved in the mechanical deformation process. Additional, previously unreported details of the behavior, evident from observing the information from the two techniques individually, are discussed.

From the work reported here it has been concluded that:

(1) Acoustic emissions above the background level occur almost exclusively before yield in 1100H, 6061 T6, 2024 T3 and 7075 T651 aluminum alloys.

(2) Acoustic emissions before yield are recoverable and different in nature from those lower in intensity occurring after yield in 7075 aluminum alloys.

(3) Monitoring of acoustic emissions of levels comparable to background reveals a maximum in such activity around 3% strain.

(4) Ultrasonic attenuation changes were observed to occur after yield in 1100H, 6061 T6, 2024 T3 and 7075 T651. The regions of most rapid change were just after yield and at the beginning of load drop.

(5) Local variations in attenuation of as much as an order of magnitude with an increase in length of less than 0.01 cm were seen to be superimposed on the average attenuation changes in all of the alloys tested. The fluctuations were most pronounced in the higher strength alloys and were sensitive to elongation rate.

To those excited by the mysteries of God's world

ACKNOWLEDGEMENTS

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Mrs. Corinne Harness through her patient typing was indispensable.

The love of my family and friends was a comfort.

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INTRODUCTION

Materials and the study of their physical properties have fascinated mankind for thousands of years. Throughout history the methods of investigation have changed and improvements have been made in sensitivity so that at present it is possible to examine in detail nearly every aspect of the mechanical deformation of materials. Two techniques which have been shown to be particularly sensitive to microstructural alterations associated with deformation are Ultrasonic Attenuation(1) and Acoustic Emission Monitoring(2).

Ultrasonic Attenuation

Listening to the sound fade out from a bell that has been struck might cause one to wonder as to the reason for this loss of energy. A similar attenuation in energy is also observed at higher, inaudible frequencies.

Various mechanisms can contribute to the energy loss experienced by ultrasonic stress waves propagating in metals. Among these are thermoelastic or heating effects, grain boundary scattering, stress induced ordering, electronic damping, acoustic diffraction, dislocation damping, ferroelectric and ferromagnetic domain damping, and scattering by point defects. However, the only loss mechanism which is markedly altered by mechanical deformation is dislocation damping. This mechanism has been considered from a variety of viewpoints, theoretical and experimental.

The possible relationship of dislocations to damping losses in metals was originally suggested by Read in 1937(3). Koehler(4) later proposed and developed the idea that a dislocation line segment might vibrate under the influence of an alternating stress field, analogous to a vibrating string. Soon after, Granato and Lücke(5) framed in further detail this "vibrating string" model. Additional ideas have been proposed by Nowick(6), Weertman(7) and others, however, the model of Granato and Lücke remains most widely accepted and in closest agreement with the results of experiments.

Although studies have been made in various materials in an effort to establish a theory, we shall be concerned only with those which relate ultrasonic attenuation to the mechanical deformation of aluminum alloys because of their face centered cubic structure, widespread practical application and role in previous investigations where either ultrasonic attenuation or acoustic emission monitoring was used.

In 1956 Hikata et al.(8) reported that in 2S and 11S Aluminum, the attenuation of a 5 MHz ultrasonic wave as a function of strain resembled the load versus strain behavior; strains of less than 1.5%, only, were considered. Based on several studies in 2S aluminum employing 5 and 10 MHz ultrasonic waves, Truell and Hikata(9,10) in 1957, indicated that attenuation was nonlinear and nonreversible when the load was a linear function of strain. Furthermore, the ultrasonic attenuation during plastic deformation was in agreement with the predictions of dislocation damping theories.

Holwech(11) found in 1960 that in high purity aluminum the ultrasonic attenuation is independent of frequency over the range 2.5 to 12 MHz. Following this, considerable work involving aluminum single crystals was done to examine more fundamentally the ultrasonic attenuation in terms of dislocation motion.

Increases in attenuation in the 10 to 13 MHz range, prior to yield in tension of aluminum single crystals, were seen by Hikata et al.(12) in 1962. In addition they indicated that attenuation changes due to plastic deformation (less than 1.5% strain) were sensitive to crystallographic orientation. Swanson and Green(13), early in 1964, measured the ultrasonic attenuation of 10 MHz waves in aluminum single crystals up to 6% strain. Their results in compression were in good agreement with those in tension of early workers. Examining the attenuation of both quasishear modes in crystals oriented for single slip caused Sachse and Green(14) to suggest that dislocation motion occurs on additional slip systems besides the primary one. In further studies on aluminum single crystals Sachse and Green(15) investigated the effects of strain rates ranging from 2×10^{-5} sec^{-1} to 20 sec^{-1}. The attenuation data exhibited marked strain rate effects in comparison with conventional stress strain curves. Sachse and Hsu(16) expanded on this work, considering in more detail this "memory effect." Vincent et al.(17) in 1974 carried these investigations a step further, associating this "memory effect" with the interaction of point defects and dislocations.

From these studies it is clear that ultrasonic attenuation is extremely sensitive to elastic and plastic deformation. This yields promise that through a greater understanding of the mechanisms associated with ultrasonic attenuation, a more complete knowledge of the fundamental nature of mechanical deformation might be obtained.

Acoustic Emission

Anyone who has broken anything is aware that certain materials when fractured emit sounds. However, the fact that this is true for less severe deformation of materials and, in particular for metals, has until recently been unknown. An exception to this is "tin cry" noise, characteristic of metal undergoing twin deformation. Not surprising then is the knowledge that the sounds which metals do indeed emit, when deformed, are of extremely small intensity and of frequencies outside the audible range.

Acoustic emission in metals has been attributed to several causes: twin formation, slip, microcracking, microvoid formation, the break away of piled up dislocations, crack growth and propagation, and phase transformations. Most of these are directly related to the mechanical deformation of metals and may be described in terms of dislocation dynamics. Experimental and theoretical studies have been performed in order to better understand the basic mechanisms which are responsible for the emission.

Several individuals have attempted to develop theories based on dislocation processes which would add insight into the mechanisms causing the acoustic emission(18,19,20). The most severe critique of these attempts has been given by Gillis(21): "The 'theory of acoustic emission' referred to in the title is almost nonexistent in the sense of quantified mathematical statements that describe a particular circumstance." It is the author's opinion that though the efforts thus far are not as bad as Gillis describes, they are for the most part in need of definitive experimental results on which to build.

Even if one restricts attention to investigations involving acoustic emission in aluminum alloys, a reasonable historical development of the understanding of this phenomenon may be seen.

In 1953 Kaiser(22) reported extensive investigations on aluminum and other materials in which he monitored the stress, or acoustic waves generated by materials undergoing mechanical deformation. He concluded that the emissions were intimately related to the deformation, but were irreversible in nature, being to a large degree absent upon reloading of the samples. This distinctive lack of emission on reloading, until the previous maximum load level is surpassed whereupon acoustic emission activity resumes, has become known as the "Kaiser effect." The potential of this study was eventually realized and many others began to actively pursue investigations in this area. Among the early work was that of Schofield(23) in the early 1960's. He reported two distinct

types of acoustic emission from aluminum, burst or individual emission and continuous or nearly simultaneous occurrence of many emissions. Tatro and Liptai(24,25) examined the influence of load and surface removal on acoustic emission behavior of aluminum copper alloys. They observed emission near yield and a marked effect of the surface conditions on the emissions. Schofield(26) continuing his work, reported in 1963, that the break away of dislocation pileups seemed to be the primary source of the emissions observed. Acoustic emission activity well before yield of 7076-T6 aluminum was seen by Dunegan et al(27) in 1968. Further investigations in 7075-T6 aluminum by Engle and Dunegan(28) suggested a correlation between emission rate and the mobile dislocation density. Sankar et al(29) noticed that in aluminum alloys displaying an appreciable Bauschinger effect the Kaiser effect was absent. Interestingly, Hartman(30), early in 1974, gave evidence that acoustic emission activity occurred most frequently at strain hardening transitions in fully annealed 1100 aluminum. At the same time Hamstad and Mukhujee(31) considered the strain rate dependence of 7075-T6 aluminum over the range 0.015 min^{-1} go 0.230 min^{-1}. They found that the rate of acoustic emission increased almost linearly with strain rate and peaked at about 3.5% strain at any one strain rate. In 1975 Hatano(32) reported that acoustic emission in aluminum single crystals was effected by an increase in the number of dislocations. Ono and Ucisik(33) examined several aluminum alloys and found their overall acoustic emission behavior to be

similar. About the same time Graham(34) indicated that the burst type emission observed prior to yield in aluminum alloys was related to the fracture of intermetallic inclusions. Furthermore, the ductile rupture of the aluminum matrix appeared to produce no detectable acoustic emission. At present much effort is still being spent in order to categorize and explain the acoustic emission of materials undergoing mechanical deformation.

Ultrasonic attenuation and acoustic emission monitoring have been extensively exploited in basic research experiments concerned with obtaining information about the microstructural changes causing plastic deformation, microcrack formation, crack growth, and fracture and in applied technical investigations concerned with detection of defects causing failure in structural materials. Theoretical treatments have also appeared in which observed experimental results from both techniques are attributed to similar deformation mechanisms. Yet, only one brief study(35) previously has employed the two techniques simultaneously.

Effort has been devoted here to comparing the results obtained utilizing these two methods, in light of earlier findings, in an endeavor to further elucidate the fundamental mechanisms involved in the mechanical deformation process. In addition, previously unreported details of the behavior, evident from observing the information from the two techniques individually, are discussed.

EXPERIMENTAL CONSIDERATIONS

Due to the extreme sensitivity of the two testing techniques used in this study caution was necessary to avoid introducing spurious effects. Several areas received special attention.

Ultrasonic Attenuation Monitoring

Fundamental to the application of the "pulse echo technique" to ultrasonic attenuation studies was the initial realization by Huntington(36), Mason and McSkimin(37) and Roth(38) that it was possible to generate a short ultrasonic pulse in a specimen in the megacycle frequency range. Extensive use has been made of the pulse echo technique in both basic research and industrial applications and was the method employed in the work reported here.

A transducer with a piezoelectric element whose crystallographic orientation determines the type of wave transmitted, longitudinal or shear, is used as both pulser and receiver. The transducer generates a pulse in the specimen which travels through the material and is reflected from the opposite face. This reflected pulse travels back through the specimen where a negligible amount of the energy from the pulse may be converted into electrical energy by the transducer, in the receiving mode, and displayed on an oscilloscope. Successive reflections or echoes of the same pulse may be displayed and compared making apparent the attenuated amplitude of the pulse. The early investigators using the pulse-echo ultrasonic technique encountered numerous problems and by reference

to their reports(37,39) similar difficulties may be avoided.

In employing this method it is imperative that the surfaces of the specimen be flat and parallel, thus avoiding wedge effects. If the specimen is to be deformed care must be exercised to assure that these conditions are maintained throughout the deformation. Furthermore, it is necessary to realize that in polycrystalline materials scattering due to the grains, inclusions and absorbing mechanisms present prior to deformation help dictate the frequency of ultrasound used. This is because attenuation may initially be so great that no echo pattern may be observed at certain frequencies. To assure understanding, it should be pointed out that the scattering due to the grain structure is the result of a variety of factors. Not only are there reflections and mode conversions because of the difference in crystallographic orientation at the grain boundaries but the direction of the energy flux vector associated with the propagating stress wave depends on the particular elastic moduli of the material. The elastic behavior in turn is a function of the grain's crystallographic orientation and is different for different grains(40). Through proper selection of frequency these problems may be minimized.

Coincident with these restrictions on frequency, imposed by the material, are those required by geometry. Empirically it has been shown that the diameter of the specimen must be several wavelengths in size in order that excessive mode conversion not occur. Overall specimen size is also a limitation in view of the fact that

absolute attenuation increases with distance due to the factors previously discussed.

Whereas the preceding restrictions are imposed by the material and its geometry there are those which are related only to the equipment. The piezoelectric transducer, though the smallest component in the system, is the object of greatest consternation. This is due in part to the variability encountered in coupling the transducer to the specimen. Several methods are used: epoxying of the element directly to the specimen, spring loading of the transducer to the specimen (intermediate in this arrangement is an impedance matching liquid couplant) or submersion of the specimen in a liquid bath. However, the reproducibility attainable in each case is poor considered in terms of the sensitivity of the overall measurement, with the previously mentioned wedging effects a constant annoyance here as well. The transducer, in addition, should empirically be several wavelengths across in order to generate a clean pulse. Work has been progressing on development of a transducer which avoids these problems as it need not be in contact in order to operate, e.g. Kawashima and McClung(41). Nevertheless, an absolute measurement of attenuation is difficult and is avoided in this work by considering only changes in attenuation.

A restriction due to the system is the pulse repetition rate. This, along with the electronics of any "continuous" monitoring equipment used, determines the responsiveness of the system. Since

no equipment responds immediately, each system averages the attenuation over some small time interval; a fact which must be kept in mind when evaluating the measurements. Instantaneous attenuation measurements are possible by photographing individual echo patterns, however, this is painstaking and discontinuous.

Bearing these restrictions and difficulties in mind, as long as care is exercised, the full sensitivity of this technique may be realized.

Acoustic Emission Monitoring

Instrumental to Kaiser's discovery of acoustic emission was the detection system he used. Since then a variety of systems have been employed, however, incorporated in each are several basic features. These include a piezoelectric sensor coupled to the material, from which any signals are then amplified, filtered and analyzed. The specifics of the system to a large extent depends on the individual experimenter's intuitive comprehension of the mechanisms causing the emission in the material under study. Still, unlike ultrasonic techniques which are active in their investigation, acoustic emission monitoring is passive and independent for the most part of the specimen geometry and material with regard to sensitivity. However, the sensitivity is crucially dependent on several other factors. Depending on the loading system and laboratory environment considerable unwanted background noise may be detected. Fortunately, the specimen can be well isolated by modified gripping arrangements from the loading system, which, in

turn, may be adapted to provide quiet loading. Some investigators assume that original stressing of the loading and gripping system to a level above the operating range will, because of the Kaiser effect, insure quiet subsequent operation. Yet, as was suggested by Duke and Kline(42) and later demonstrated by Kline(43) acoustic emissivity may be restored due to recovery at room temperature, thus making this previous assumption at times erroneous. For research purposes the aforementioned changes are feasible, but they are in general unreasonable in most field applications. Alternative measures which are possible because of the nature of the frequency of the acoustic emission involve selective filtering to eliminate both background and loading machine noise. With these obvious interferences removed the sensitivity is limited only by the electronic noise which is dependent on bandwidth and amplification of the system. Intimately related to the bandwidth and system gain selection is the choice of piezoelectric sensing transducer. Difficulties in coupling of the transducer to the specimen similar to those encountered with ultrasonic techniques are prevalent. Again, lack of reproducibility is a major problem, since at present no standard method for generating acoustic emission signals exists to even allow for comparison. This fact also makes absolute system gain standardization from test to test difficult. As a result of the absence of an artificial emission source no standard method for transducer calibration is universally accepted and utilized by manufacturers and researchers. A method developed at the National

Bureau of Standards by Breckenridge et al(44) seems to offer promise for partially filling this void. Palmer and Green(45) at the Johns Hopkins University, however, are progressing on an innovative technique which, though in the very early stages of development, should allow for absolute calibration. It will allow for extremely sensitive contactless detection by making use of an interferometric optical arrangement.

Certain limits are placed on the overall sensitivity by the electronic components such as filter rolloff and attenuation, amplifier dc level drift and the overall systems dynamic range. These problems are peculiar to individual instruments and shall not be elaborated on here. However, considering the constantly advancing electronics field, improvements can be expected.

Nevertheless, with the fruition of these advances still in the future, by paying heed to the aforementioned difficulties, good measurements may still be made.

EXPERIMENTAL PROCEDURE

Specimen Preparation

One inch diameter rod stock of various commercial aluminum alloys (1100 H, 6061 T6, 2024 T3, 7075 T651) was machined to have a reduced gauge section in a "dog bone" configuration. Several different specimen sizes were employed and are listed in Table I which refers to Fig. 1.

TABLE I

	Type 1	Type 2	Type 3
a	0.625 in.(1.59 cm)	0.625 in.(1.59 cm)	1.0 in.(2.54 cm)
b	2.0 in.(5.08 cm)	2.0 in.(5.08 cm)	4.0 in.(10.16 cm)
c	0.625 in.(1.59 cm)	0.625 in.(1.59 cm)	0.625 in.(1.59 cm)
d	0.5 in.(1.27 cm)	0.4 in.(1.02 cm)	0.4 in.(1.02 cm)
e	3.25 in.(8.26 cm)	3.25 in.(8.26 cm)	5.625 in.(14.29 cm)

For specimens of all three types the shoulder was machined to have a small 0.094 in. (0.24 cm) radius in order to avoid excessive stress concentration in these areas while loading. The end faces were machined flat and parallel.

Testing of a few specimens which had been annealed served to provide the preliminary organizational procedure necessary due to the number of simultaneous measurements which had to be made. Aside from these specimens only two others were thermally treated. A type 3 specimen of 7075 T651 was given a T6 treatment(46) in order to judge the effect, if any, of small variations in thermal history. Etching for 30 seconds in Keller's reagent(47) was sufficient to remove the

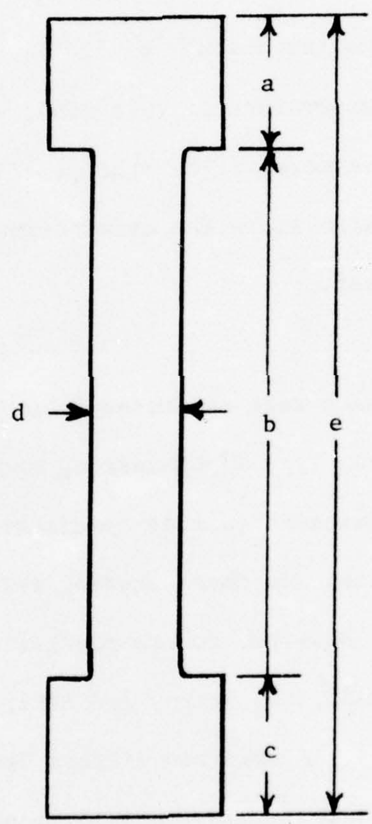


Fig. 1. Schematic of Specimen Design

oxide formed during the treatment. To insure smoothness of the end faces they were polished on No. 600 grit paper. A second 7075 T651 type 3 specimen (Test C4), was placed in a furnace at 130°F (55°C) for 80 hours. Prior to this treatment the specimen had been loaded and unloaded twice to 3250 Kg, then allowed to recover at room temperature 72 hours and reloaded to 3250 Kg. In an effort to accelerate recovery the temperature of 130°F, half of the precipitation heat treatment temperature of 7075 T651, was chosen; the time span was arbitrarily selected. The other specimens were subjected to no further preparation since the examination of commercial products was the primary interest.

Loading System

All of the specimens were subjected to uniaxial tensile loading by a Floor Model Instron Type TT-CM testing machine. Being a "hard" machine the Instron nominally extends specimens at a selectable, constant elongation rate. In these studies rates of 0.05 cm/min and 0.2 cm/min were used. However, due to elastic compliances in the load cell monitoring unit, the grips, and other parts of the system, the actual extension of the specimen differs from that plotted by the Instron recording unit. These contributions can be determined by directly loading the system without the specimen and then subtracting the extension, which is a function of load, from the load versus extension plot obtained when the specimen is deformed. Furthermore, because of this elastic loading and the constant elongation, sudden

specimen yielding is manifested as a load drop. The load cell, Instron Model FM Tensile-Compression, operated in the least sensitive, maximum capacity 5000 Kg range was correlated to a clip gauge response to determine the adequacy of its sensitivity. Examination of the results indicated that the Instron load recording system was adequate for the elongation rates used.

In order to couple the grips to the load cell an universal, flexible coupler or rigid coupler was used; the crosshead coupler was rigid in every test. The different couplers were employed to assure that no flexure of the specimen occurred during deformation, since this would cause spurious ultrasonic results.

It was necessary for the grips to be compatible with both couplers. This posed no real difficulty since the couplers were similar and the grips, Fig. 2, were specifically designed for this study. The major design criteria were that easy access be provided at either end of the specimen for transducer placement, uniform uniaxial application of the load and reasonable acoustic isolation from the loading machine. A cage-like design of two 0.75 in (1.91 cm) thick plates, one of which was slotted to accept the specimen, connected by four 0.75 in (1.91 cm) diameter rods of steel was chosen. A split steel collar was used to accurately align the specimen as well as distribute the load. Teflon washers were placed under the main load supporting shafts to provide acoustic isolation, however, due to the band pass filtering employed they proved to be inconsequential.

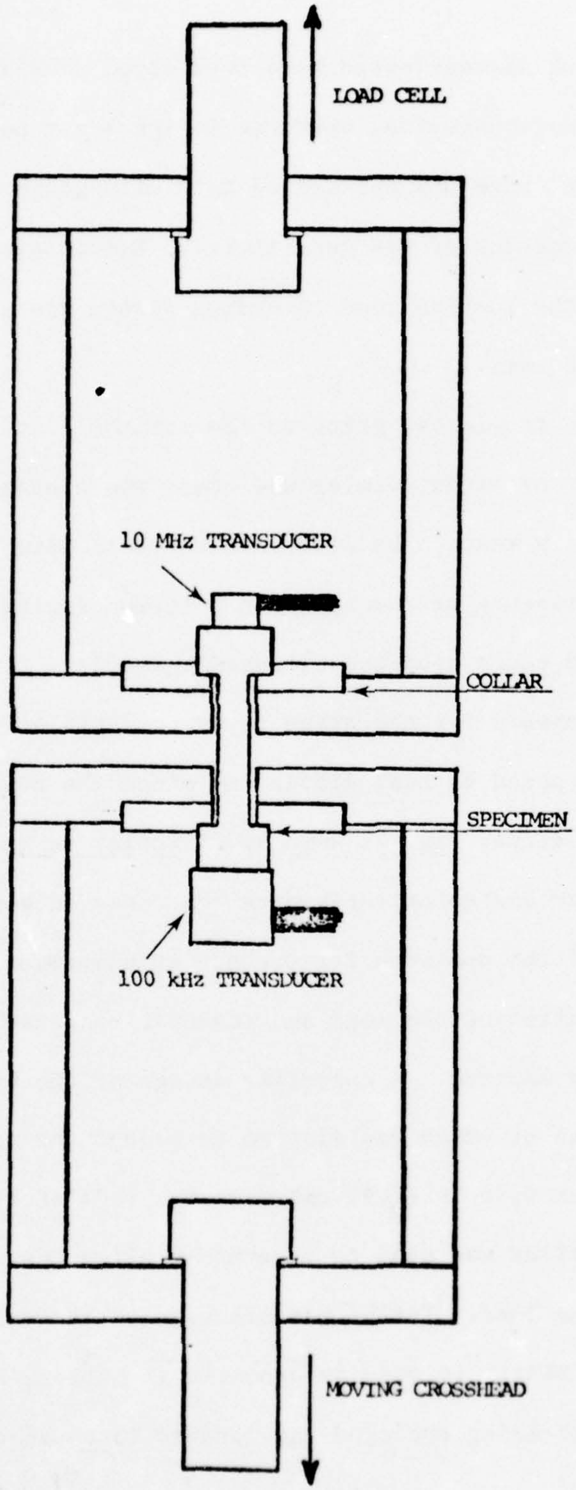


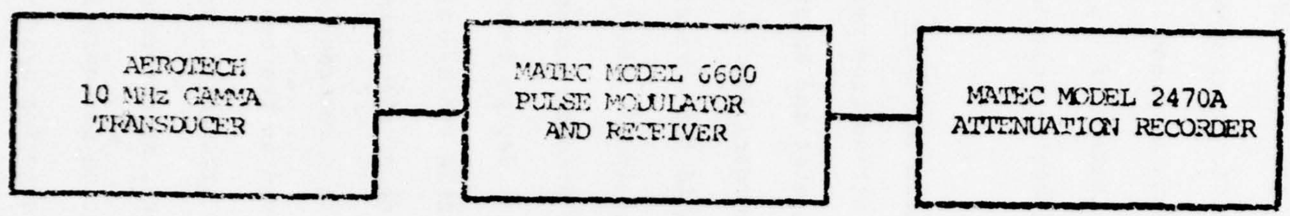
Fig. 2. Specimen Gripping Configuration

The actual loading procedure was that characteristic of any Instron machine. A minimal preload of 20 Kg was used to assure all slack was taken up, avoiding realignment of the specimen and the noise associated with such movement. No influence of the mechanical or electrical operation of the Instron on either the ultrasonic attenuation or acoustic emission monitoring was encountered.

Ultrasonic Attenuation Monitoring System

Continuous ultrasonic attenuation measurements were made by a Matec Model 6600 Pulse Modulator and Receiver coupled with a Matec Model 2407A Attenuation Recorder, Fig. 3. This system allows two echoes to be selectively gated for comparison by a logarithmic volt meter. The first and second longitudinal wave echoes were used in this study. Two and a half seconds was approximately the overall system response time. System design features are provided for recorder offsets, making possible the use of a sensitivity selection limited only by the magnitude of the attenuation change encountered during a test. The attenuation recorder plots only the attenuation, as it varies in time, observed in the two selected echoes. By subtracting out the initial attenuation value and dividing by the instantaneous specimen length, as determined from the load extension data, the change in attenuation per unit length (dB/cm) is obtained. In conjunction with this monitoring system a 0.5 in (1.27 cm) diameter Aerotech 10 MHz Gamma transducer was operated in the pulse-echo mode at a repetition rate of 200 times a second. The

Fig. 3. ULTRASONIC ATTENUATION MONITORING SYSTEM



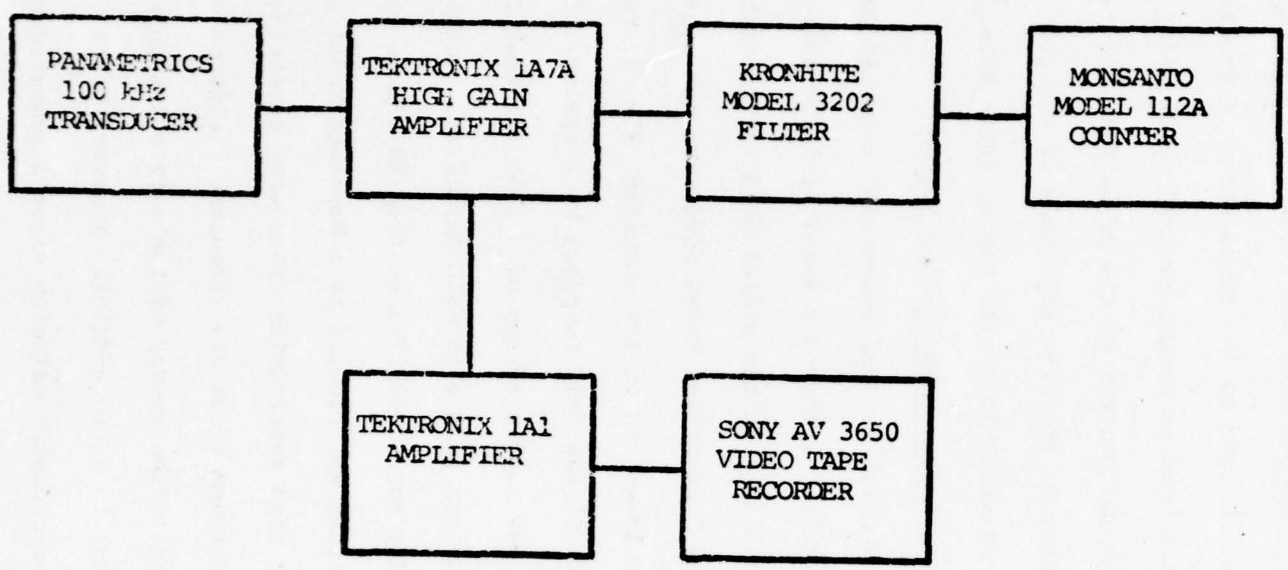
transducer was directly coupled to the upper specimen face, Fig. 2, with nonaqueous stopcock grease. A 3 Kg weight was used to supply a constant load to the transducer. A specially designed spacing ring was used to assure central positioning of it, avoiding excessive reflections of the pulse from the lateral surfaces. Care was taken so that the amplitude of the driving pulse was well below that necessary to excite the acoustic emission sensor.

Acoustic Emission Monitoring System

Although several commercial acoustic emission monitoring systems are available, they are somewhat inflexible for laboratory work. Figure 4 depicts the system used in this study. An one inch diameter 100 kHz Panametrics Model 5070 resonant sensor was coupled directly to the lower end of the specimen, Fig. 2, with nonaqueous stopcock grease; it was held in place by a spring. The signal from the transducer was amplified and band pass filtered from 10 kHz to 300 kHz by a Tektronix 1A7A high Gain Amplifier. Further filtering by a Kronhite Model 3202 Filter from 80 kHz to 120 kHz occurred before the signal was counted by a Monsanto Model 112A Counter.

A high sensitivity transducer operating in a very narrow frequency range about its resonance yields an output which is directly related to the energy of the excitation pulse, when threshhold counting is performed(48). However, because of the extreme low level of some acoustic emission signals compared with the electronic noise, the only resort is rate counting, or root mean square voltage monitoring.

Fig. 4 ACOUSTIC EMISSION DETECTION SYSTEM



In the initial stages of deformation of aluminum alloys burst type emission, conducive to threshold counting, occurs but rate counting must be used to quantify the continuous low intensity emissions which appear during the latter stages of the deformation. Visual evidence of the rate change may be seen by observing the amplitude of the background signal on an oscilloscope or on playback of a recording of the signal.

When recording of the signal by a Sony AV 3650 Video Tape Recorder was done additional amplification of the Tektronix 1A7A output was provided by a Tektronix 1A1 Amplifier. A video tape recorder like the Sony AV 3650 which has rotating recording heads, making possible a large effective tape speed, is necessary in order to achieve the frequency response required to accurately record the acoustic emission signals.

In these studies threshold counting and rate counting were both employed in order to best discern the acoustic emission behavior. Recording of the signals was performed during some tests but no actual data came from analyzing these tapes.

RESULTS AND DISCUSSION

Data depicting the load (Kg), attenuation (dB/cm) and acoustic emission (counts/time) versus extension (cm) for each test is plotted separately, but in a similar format to allow for easy comparison, Figs. 5 - 18. For the tests displayed in Figs. 5 - 14, and 16 - 18 the emissions were monitored at approximately 80 dB and as such only emissions above the background noise level were detected by the counter. In each of these cases the accumulated acoustic emission counts per 15 second intervals are plotted. The crosshead speed was 0.05 cm/min for all tests except for that of Fig. 14 which was 0.2 cm/min.

Representative examples of simultaneous ultrasonic attenuation and acoustic emission monitoring tests during tensile deformation of 1100H, 6061 T6, 2024 T3 and 7075 T651 aluminum are shown in Figs. 5 - 8, respectively. As may be seen from examining the data, acoustic emission activity is predominant in the pre-yield region with little or no emission occurring after yield.

Due to capacity limitations of the testing machine, smaller specimen cross sections were necessary in order to plastically deform the higher strength alloys. Because of this, the specimen of 2024 T3 for which the results are shown in Fig. 7 was deformed to just beyond yield.

The cross section of the 7075 T651 specimen (Type 2), displayed in Fig. 8 was such to allow plastic deformation. A few acoustic emissions were observed after yield in this case but they were in no way comparable to those occurring before yield.

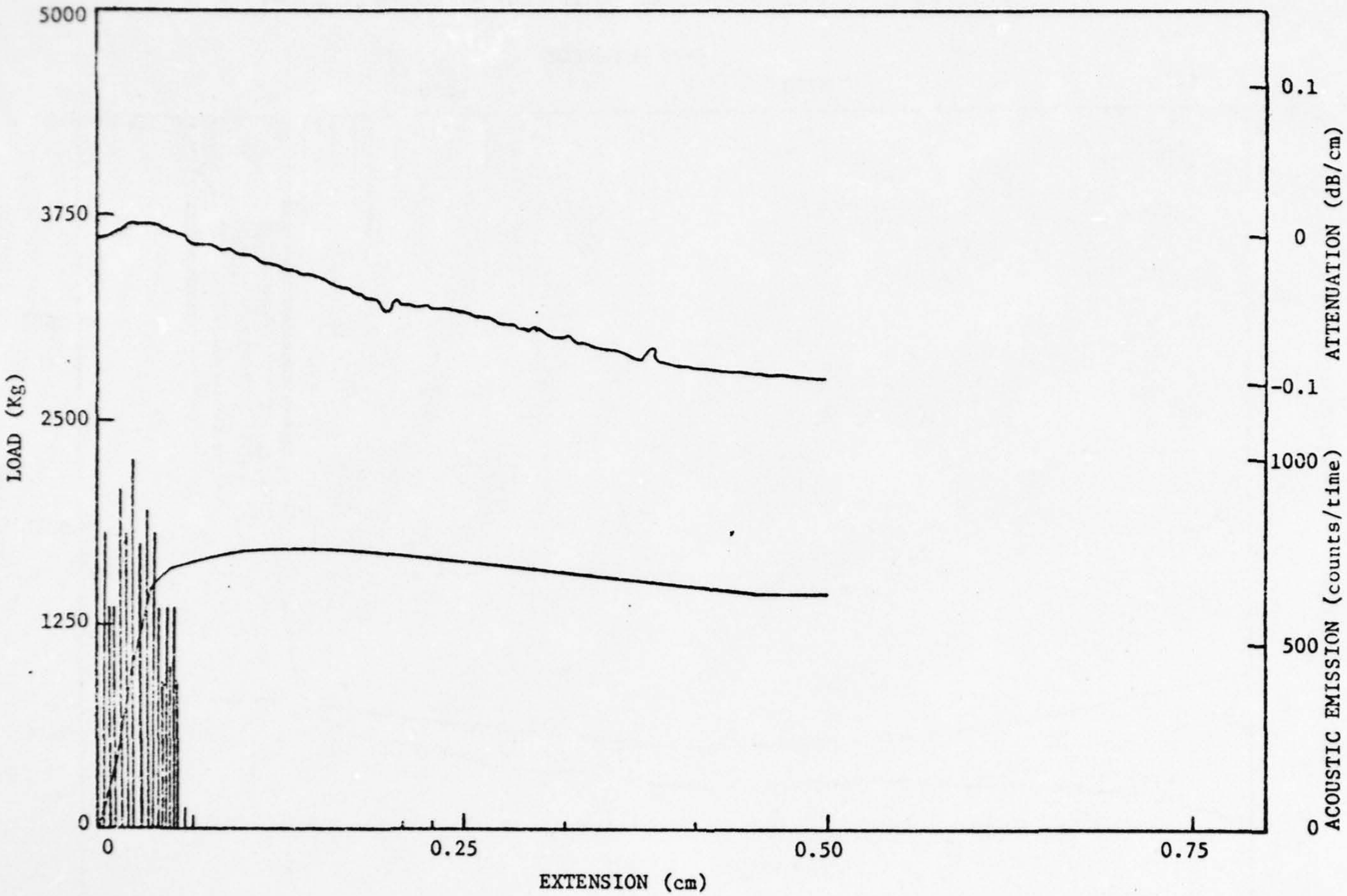


Fig. 5. Experimental Data Test A1 Type 1 1100H Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

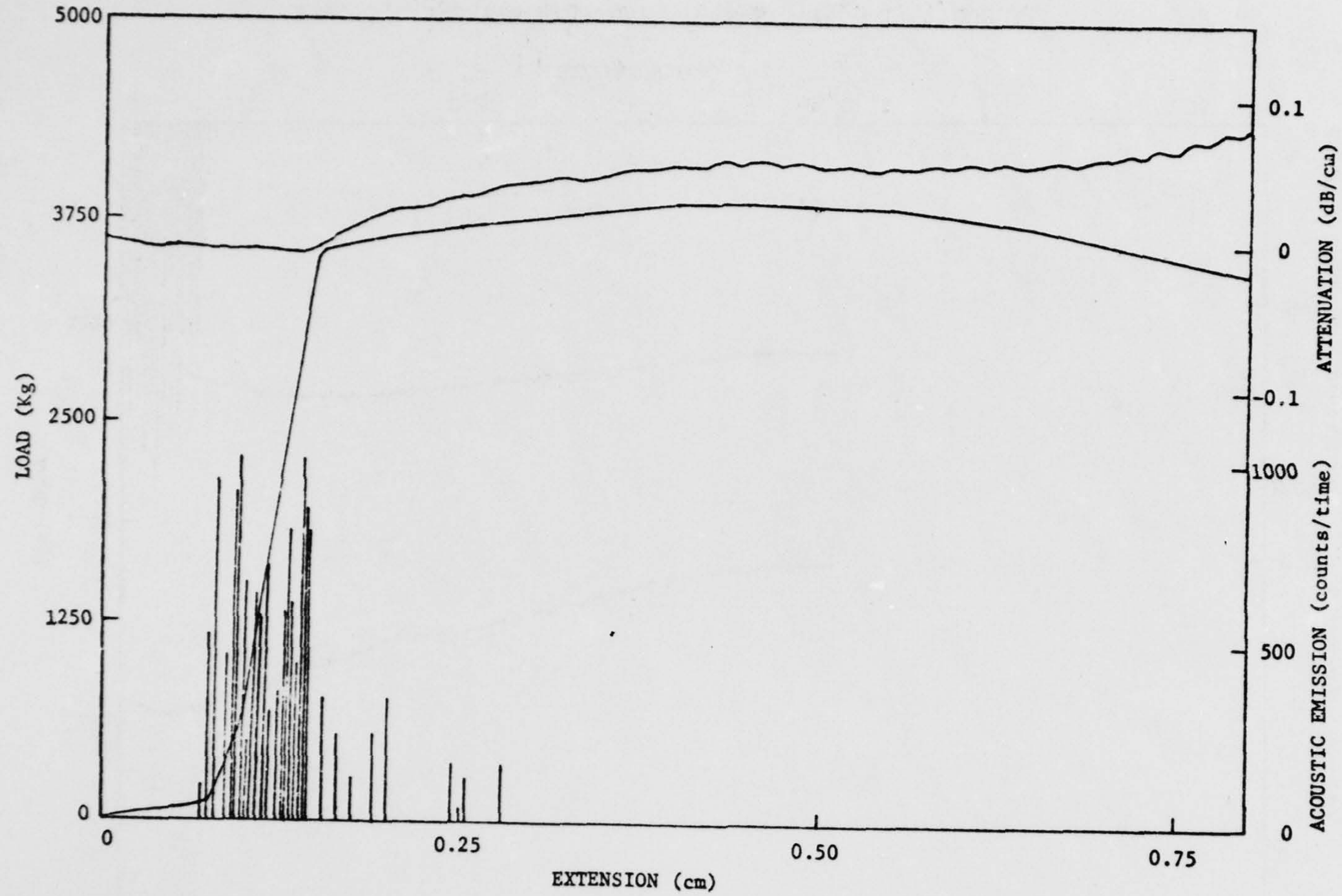


Fig. 6. Experimental Data Test A2 Type 1 6061 T6 Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

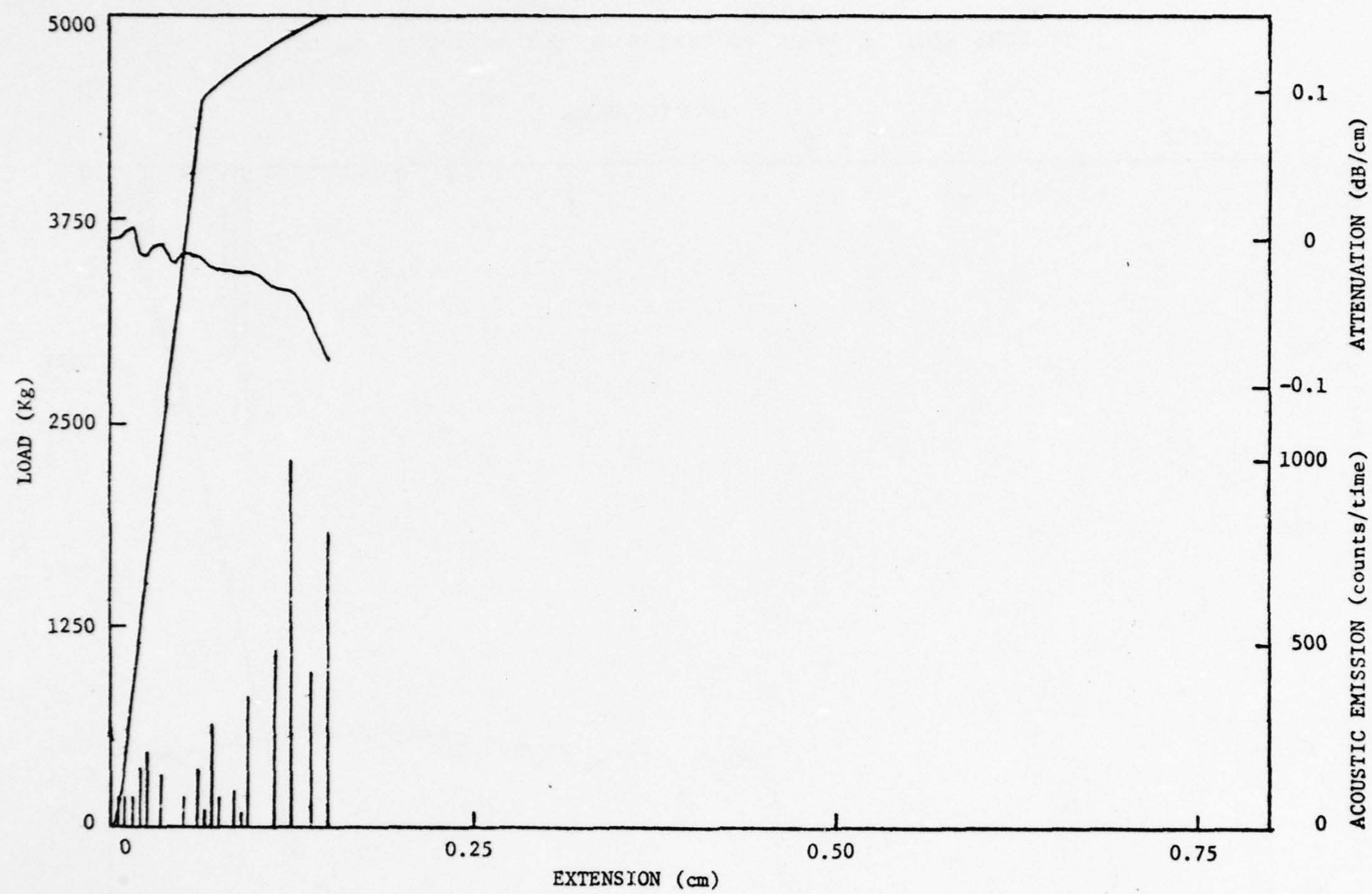


Fig. 7. Experimental Data Test A3 Type 1 2024 T3 A1
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

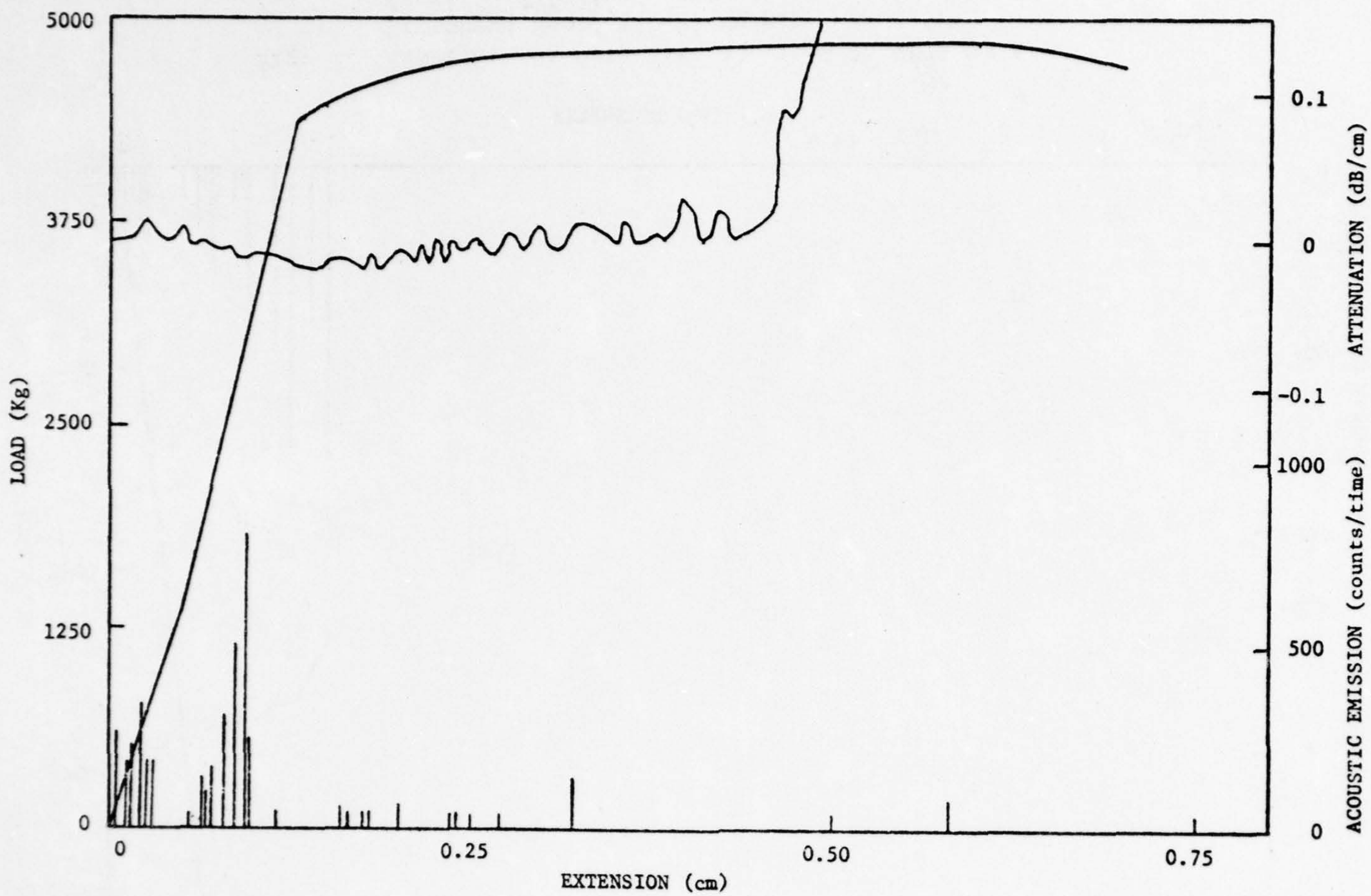


Fig. 8. Experimental Data Test A4 Type 2 7075 T651 Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

The ultrasonic attenuation, on the other hand, displayed an opposite behavior. For each of the alloys tested the change in attenuation per unit length before yield was nearly imperceptible. Upon yielding the attenuation was seen to change in every case. For 1100H and 2024 T3 the attenuation decreased, while for 6061 T6 and 7075 T651 an increase was observed. In both 6061 T6 and 7075 T651 the regions of most rapid change were at yield and at the onset of load drop. Local variations in the attenuation as a function of elongation were also apparent in these alloys. These fluctuations were most pronounced in the higher strength alloys. For instance, as may be seen in Fig. 8, the fluctuations cause the change in attenuation to vary as much as an order of magnitude with an increase in length of less than 0.01 cm. In order to examine these results in greater detail three series of tests were performed.

First, in order to determine the repeatability of the behavior of any one alloy, three further tests on 6061 T6 were performed; the results are displayed in Figs. 9 - 11. Acoustic emissions were monitored only in the first two tests. The observed behavior was identical, with nearly all of the acoustic emission occurring prior to yield. As before, the ultrasonic attenuation showed little change prior to yield. In tests B2 and B3 the attenuation increased after yield, however, in Test B1 the attenuation decreased after yield and then increased when the load began to decrease. Again the regions of most rapid change were at yield and after the load began to drop. In all three cases the local variations were present and especially

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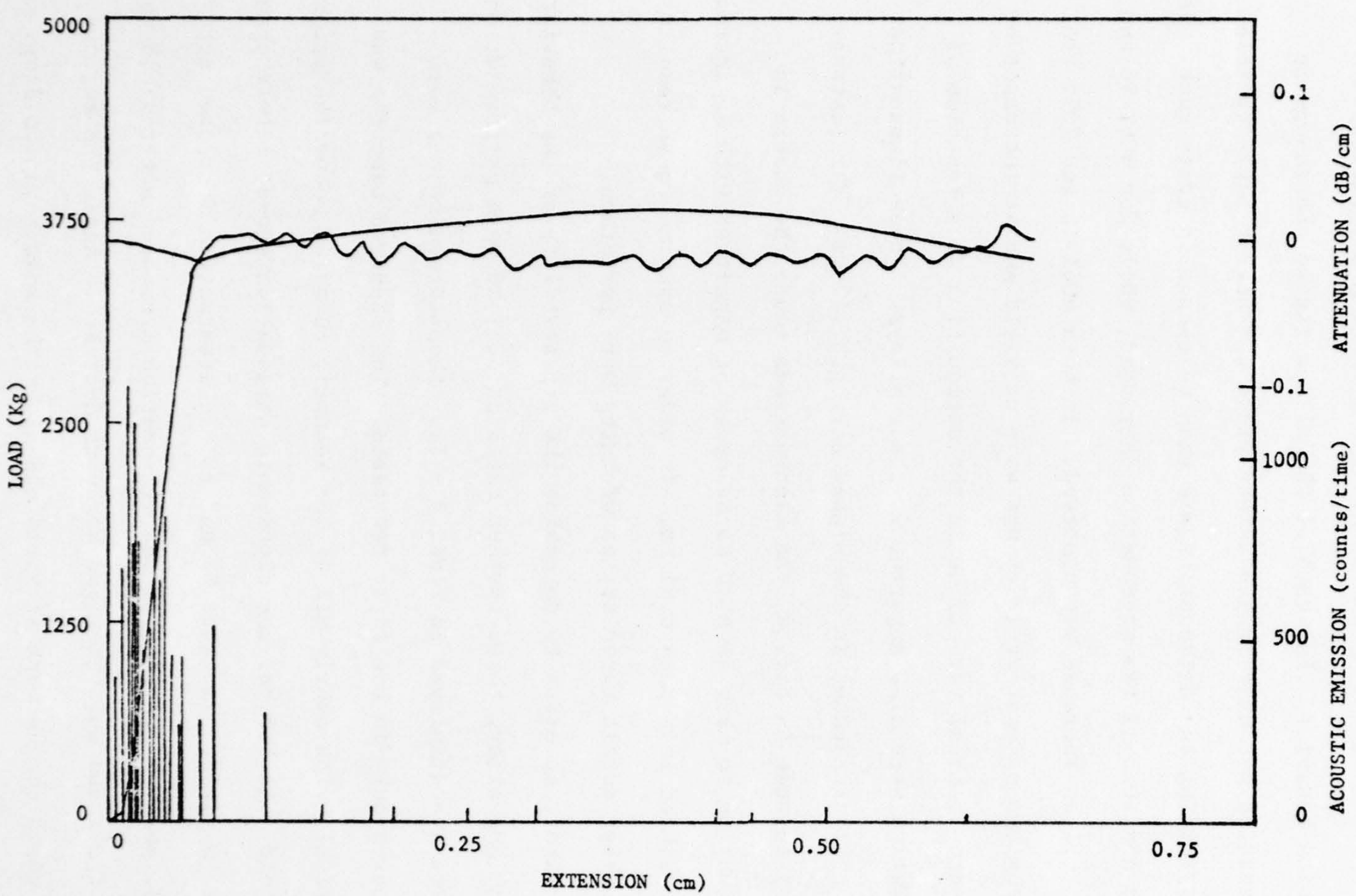

Fig. 9. Experimental Data Test B1 Type 1 6061 T6 Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

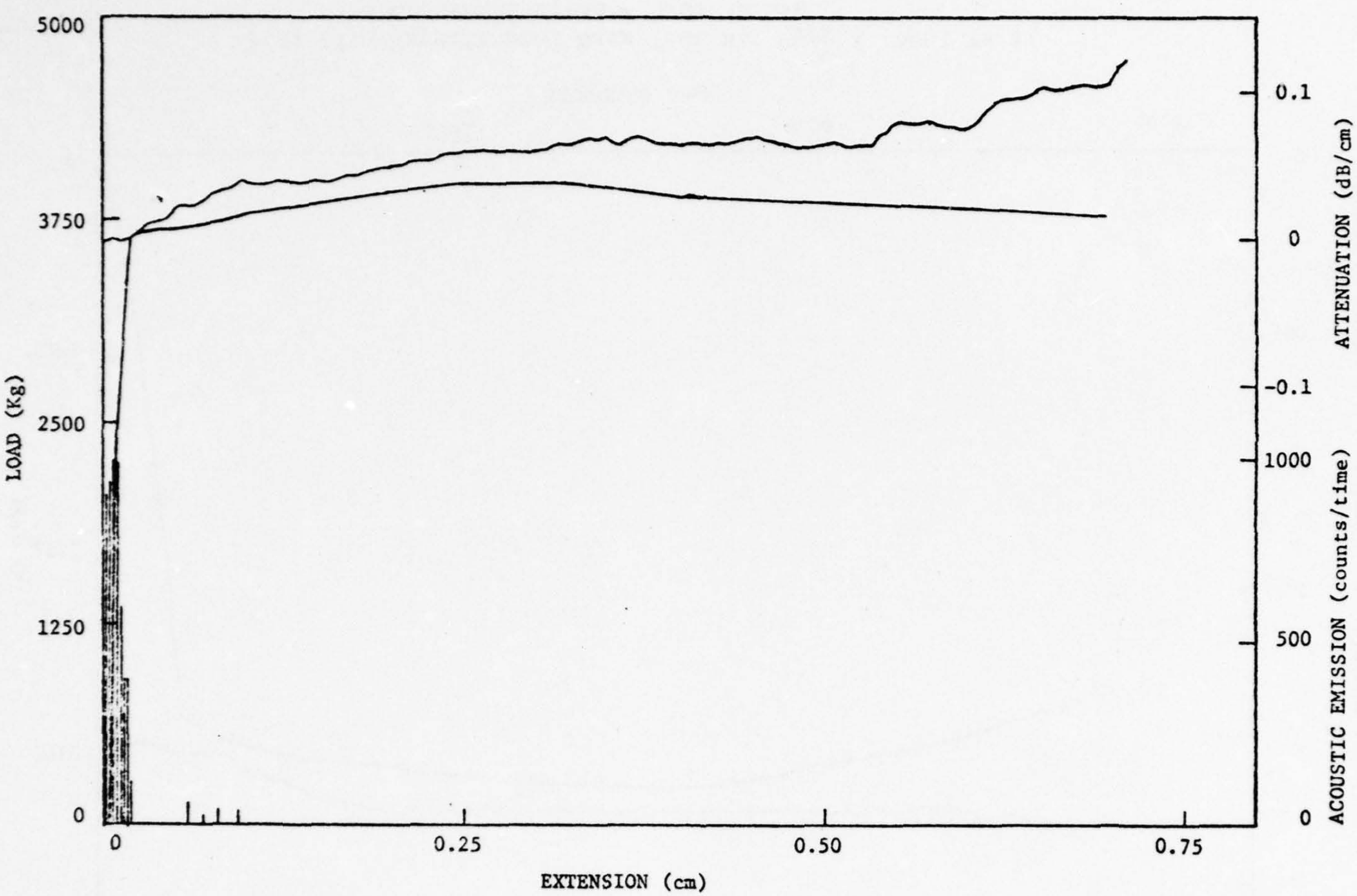

Fig. 10. Experimental Data Test B2 Type 1 6061 T6 Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

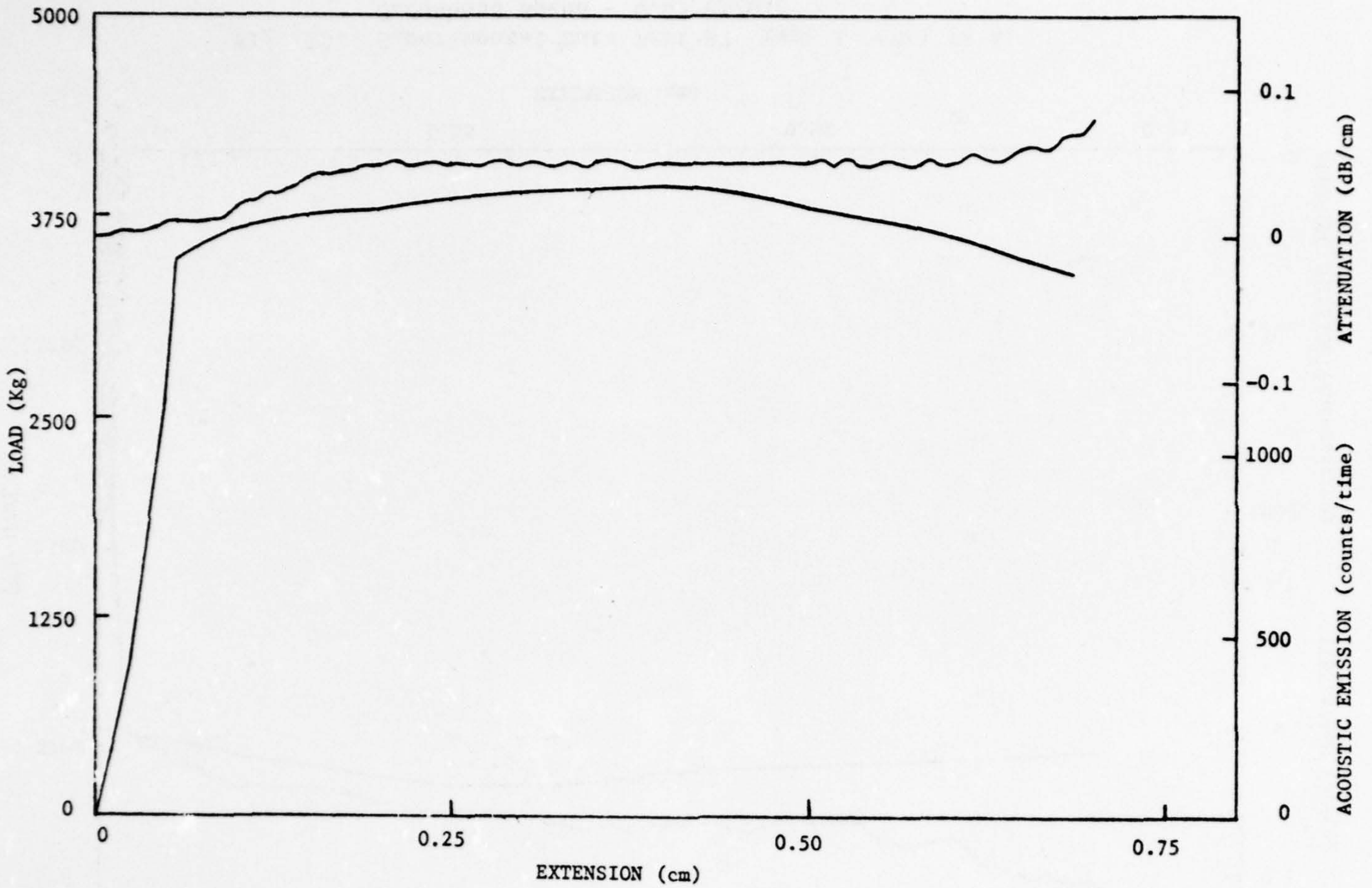

Fig. 11. Experimental Data Test B3 Type 1 6061 T6 Al
Crossshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

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prevalent in test B1. Since the most pronounced behavior in this regard was seen in the 7075 T651 alloy it was decided to make this alloy the subject of a second series of tests to further investigate these fluctuations.

The results of this series are reported graphically in Figs. 12 - 16. During these tests a major part of the effort was devoted to making certain that the fluctuations were only the result of the mechanical deformation of the test material and not some artifact introduced by the testing system. No acoustic emissions were monitored during some of these tests. Initially, two different couplers were used - an universal, flexible coupler or a rigid coupler. The test depicted in Figs. 12, 13 and 15 employed the flexible coupler, while those of Figs. 14 and 16 used the rigid one. It was felt that any flexural loading of the specimen would be changed by interchanging the couplers. No effect of the change in couplers was apparent in the tests conducted.

Tests C1 and C2, Figs. 12 and 13, were performed in an identical fashion; both specimens were type 2 and the crosshead speed was 0.05 cm/min. Although in one test the attenuation increased and in the other it decreased, the fluctuations were extremely similar being superimposed on a net change which behaved as that previously described in the case of 6061 T6. Since it was thought that perhaps the shape of the specimen was somehow related to these variations, tests C3 and C5 of Figs. 14 and 16 were performed. In test C3 a specimen of type 3 was extended at a rate of 0.2 cm/min using the rigid coupler.

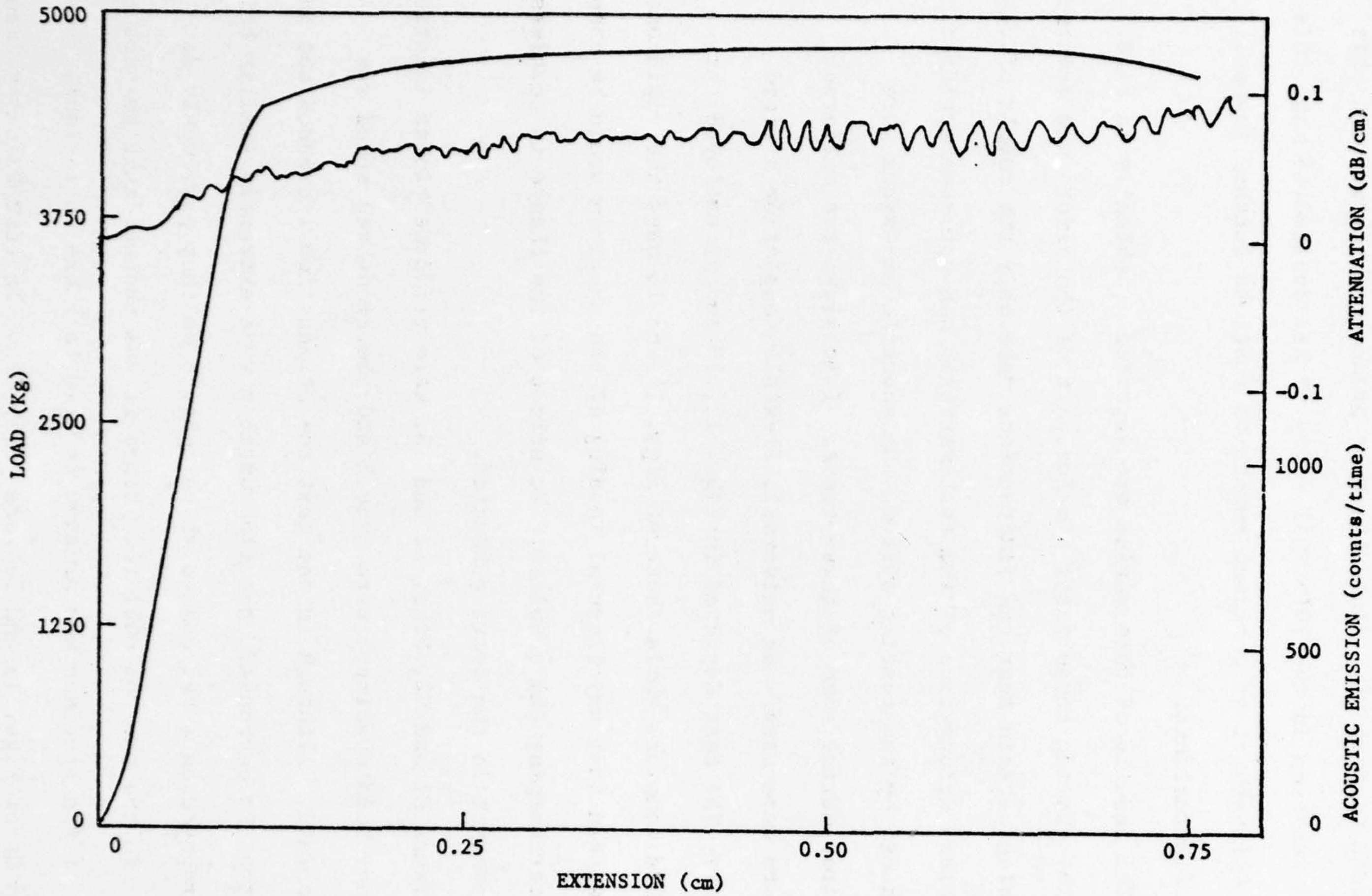

Fig. 12. Experimental Data Test C1 Type 2 7075 T651 Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

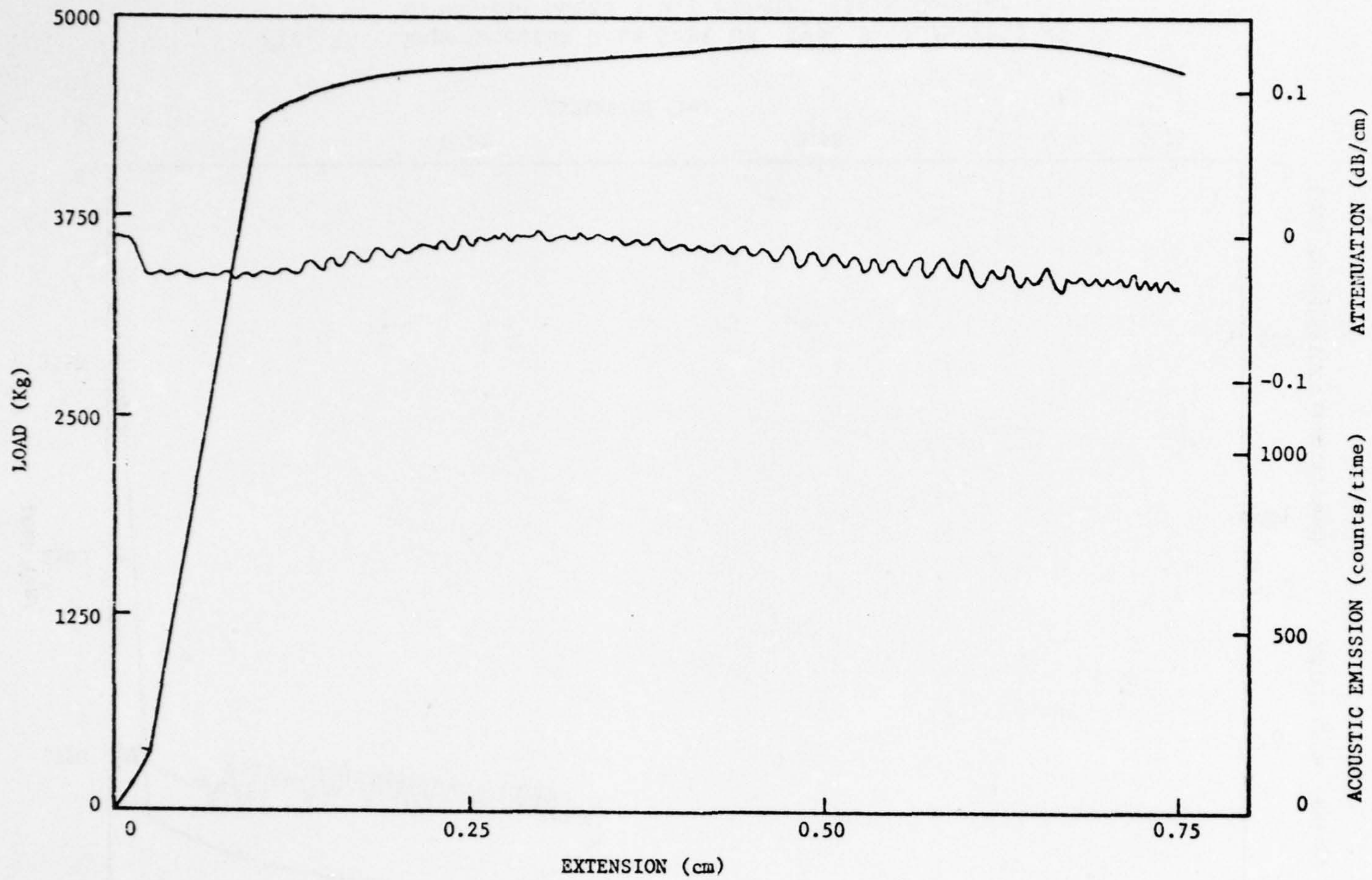

Fig. 13. Experimental Data Test C2 Type 2 7075 T651 Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/15 sec at 80 dB Gain

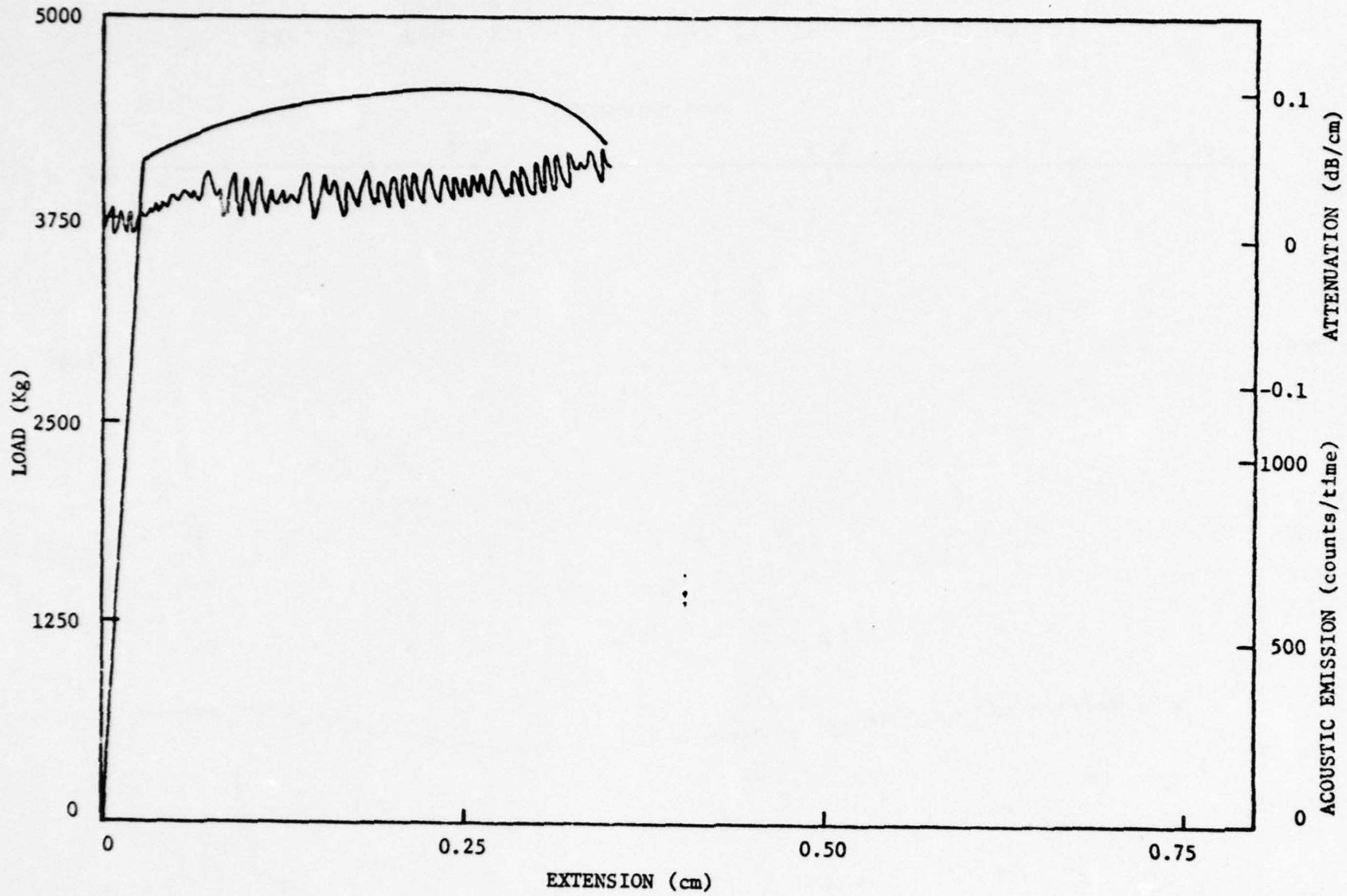

Fig. 14. Experimental Data Test C3 Type 3 7075 T651 Al
Crosshead Speed = 0.2 cm/min Rigid Coupler
Acoustic Emission Counts/15 sec at 80 dB Gain

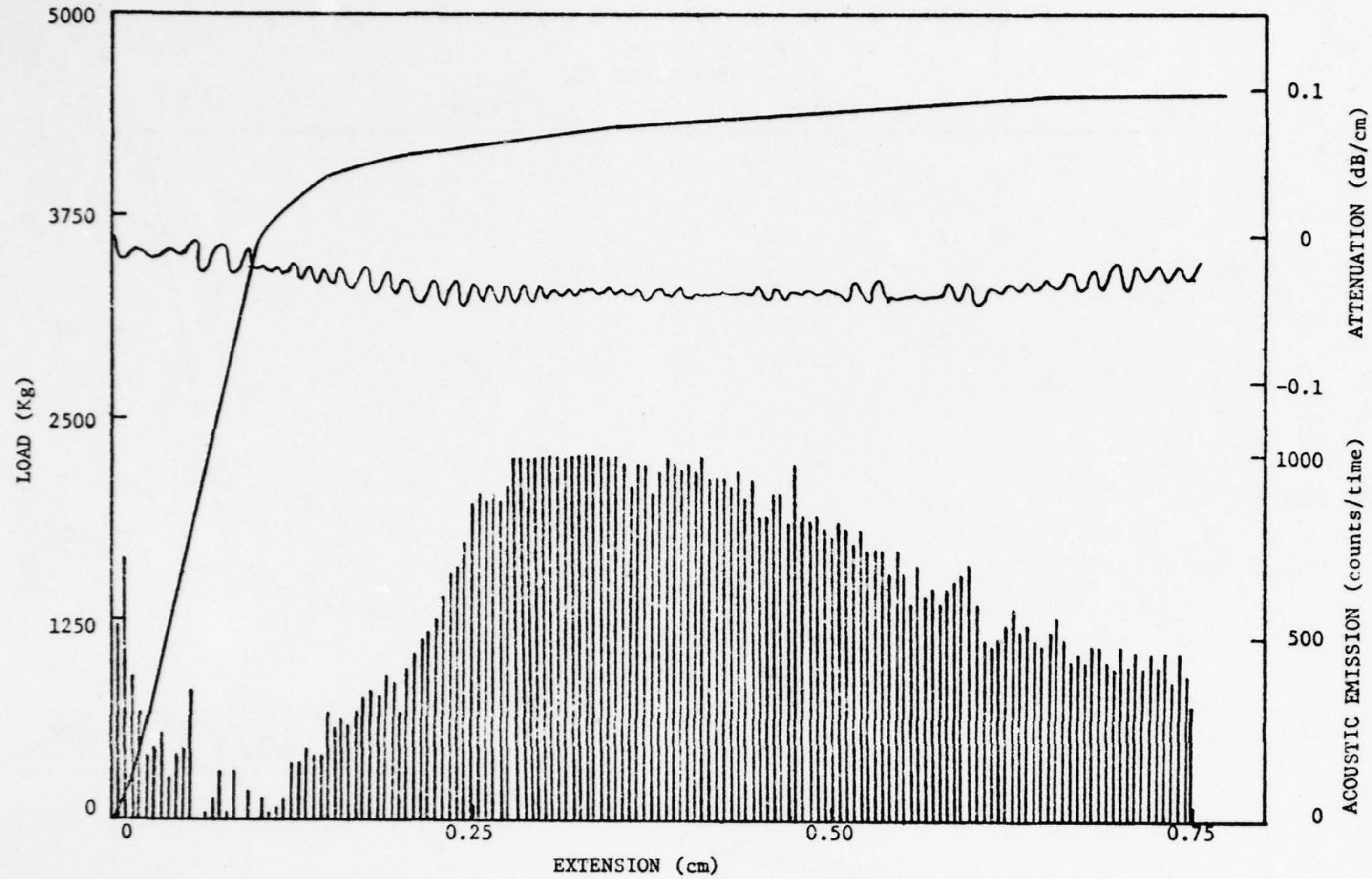

Fig. 15. Experimental Data Test C4 Type 3 7075 T6 Al
Crosshead Speed = 0.05 cm/min
Acoustic Emission Counts/1 sec at 85 dB Gain

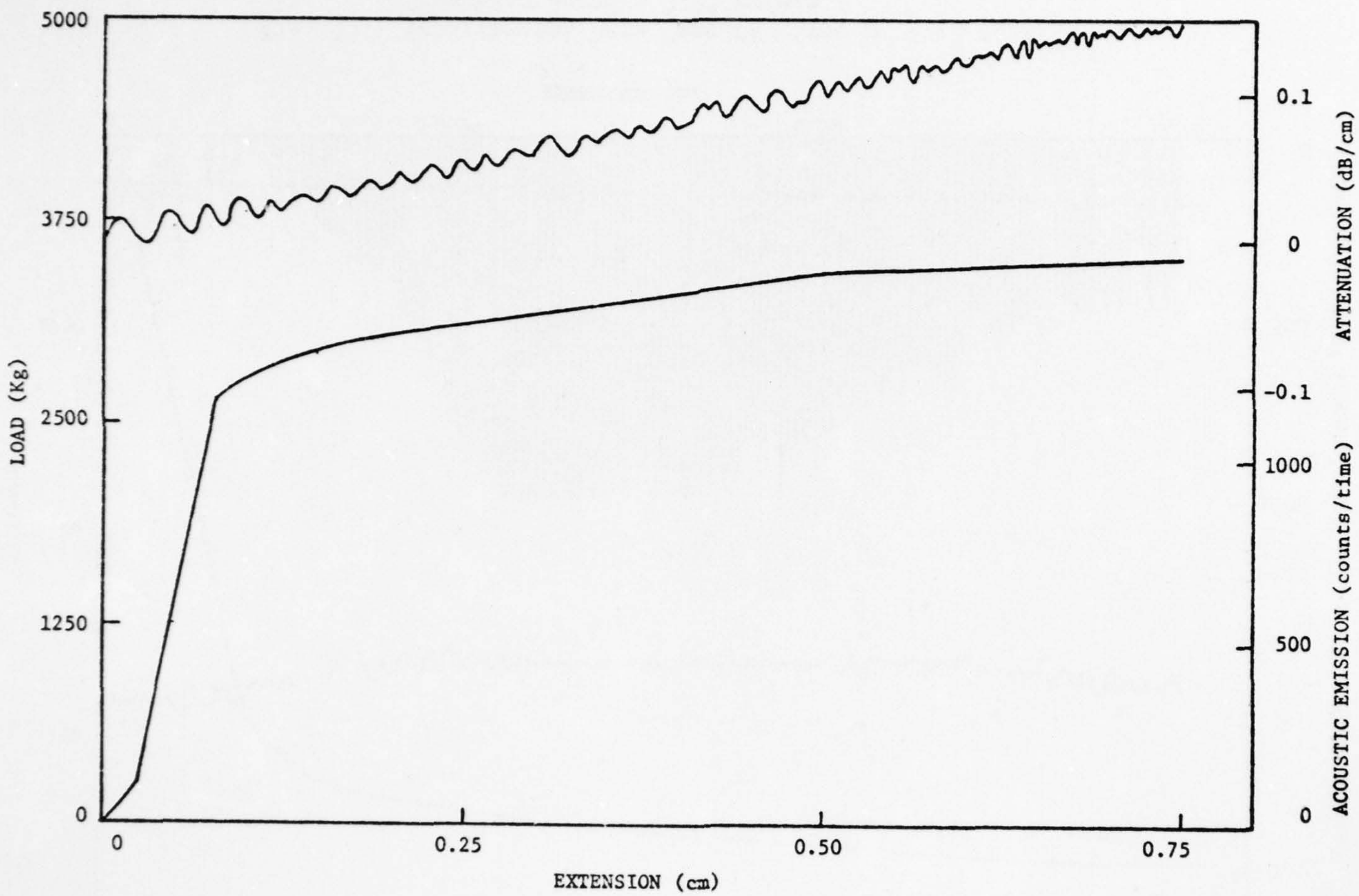

Fig. 16. Experimental Data Test C5 Type 2 2024 T3 Al
Crosshead Speed = 0.05 cm/min Rigid Coupler
Acoustic Emission Counts/15 sec at 80 dB Gain

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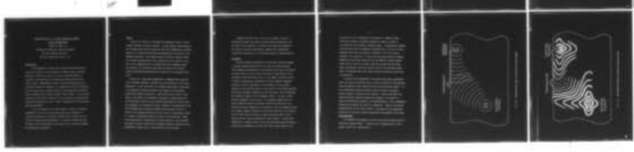

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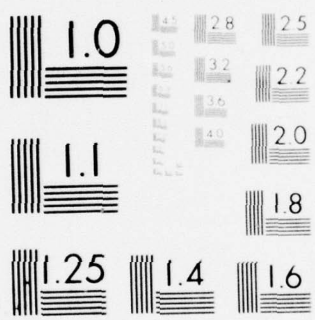

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The results indicated that although the frequency of the variations as a function of extension were the same, the magnitude was greater than those of tests C1 or C2. Test C5, Fig. 16, was performed on a type 2 specimen of 2024 T3 Al in order to determine the effect of the reduced diameter of this type specimen; the rigid coupler was again used. Variations of the change in attenuation did occur, but the details of the fluctuation were markedly different both in amplitude and frequency. One further detail which bears mentioning is the fact that fluctuations without any average change in attenuation were seen in both tests C3 and C5. In an effort to determine the effect of small variations in tempering a type 3 specimen which had been subjected to a T6 heat treatment was tested; test C4, Fig. 15. The rate of extension was 0.05 cm/min and the acoustic emission activity was monitored at a gain setting of 85 dB. Because of this increased gain setting, acoustic emission activity of an amplitude about the same as the background was detected; accumulated counts for 1 sec intervals are plotted. The average change in attenuation (the value of change in attenuation about which the fluctuations vary) was seen to decrease at yield and then increase as the load began to drop. Fluctuations in the attenuation similar in character to the other 7075 T651 specimens were observed. Although no explanation is offered for these fluctuations, it is felt that this series of tests provided strong evidence that the fluctuations are, indeed, a result of the deformation of the material.

In addition, as a result of this modified fashion of acoustic

emission detection, the previously pronounced emissions prior to yield were indistinguishable, but a maximum in the rate of emissions occurred around 3% strain (approximately 0.3 cm extension). To better discern the nature of the pre-yield emission, the third series of experiments shown in Figs. 17 and 18 were conducted. All the tests were performed on the same type 3 specimen of 7075 T651 Al and extended at a rate of 0.05 cm/min. The specimen was initially loaded to 3250 Kg, unloaded and then immediately reloaded to the same load level and again unloaded. After 72 hours, the specimen was loaded to 3250 Kg; ultrasonic attenuation and acoustic emission were monitored during all three loadings. The results of this monitoring are shown in Fig. 17. During the first loading the typical pre-yield emission activity was observed. On immediate reload, no emissions as predicted by the Kaiser effect were observed. Furthermore, no emission activity was observed after allowing 72 hours for room temperature recovery to occur. The ultrasonic attenuation as in the case of Figs. 14 and 16 was seen to fluctuate, however, unlike these two previous tests, an average increase in attenuation was observed. This average increase in the attenuation was noticeably smaller during the third loading. In an effort to speed any recovery, the specimen was placed in a furnace at 130°F for 80 hours, and then reloaded to 3250 Kg. After reloading and unloading, the specimen was loaded one final time; during both loadings the ultrasonic attenuation and acoustic emission were again monitored. Upon reloading of the specimen after the thermal treatment acoustic emissions similar to

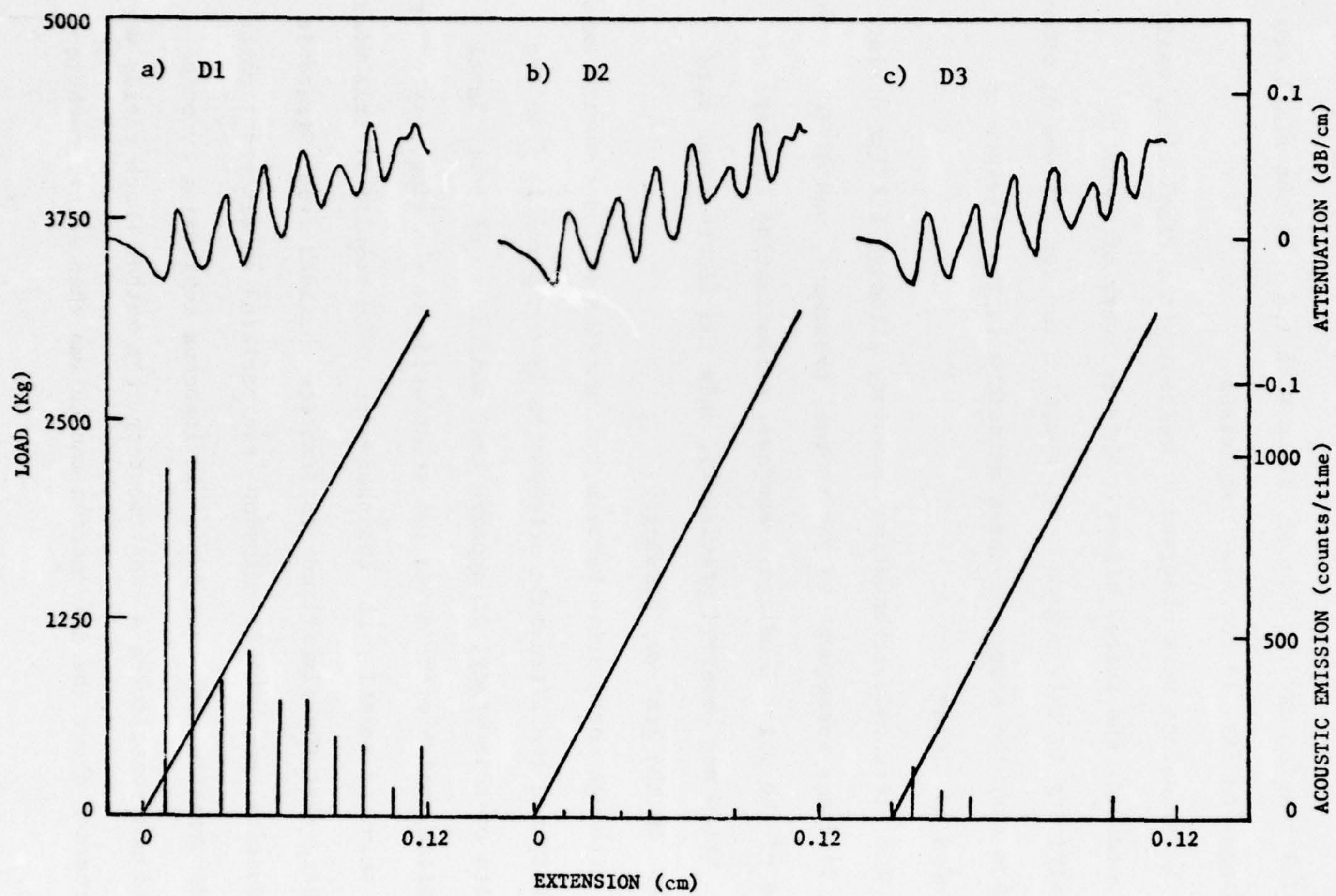

Fig. 17. Experimental Data Load-Reload Series Type 3 7075 T651 Al
Crosshead Rate 0.05 cm/min Acoustic Emission Counts/15 sec at 80 dB Gain
a) D1 Initial Loading b) D2 Reload c) D3 Reload after 72 hrs.

those of the initial loading were observed. The results of the initial loading are reproduced, along with those of the final two loadings, on Fig. 18 for easy comparison.

No emissions were observed on reloading the final time, again demonstrating the Kaiser effect. This recovery of acoustic emissitivity in this region casts doubt on the contentions of other workers that the source of these emissions is the fracture of included particles.

The ultrasonic attenuation behavior, although similar during both loadings subsequent to the thermal treatment, was different from those of the prior loadings. Whereas, a fluctuating increase of attenuation was observed previously, only the fluctuations were present in the last two loadings.

Although correlation between the behavior of the acoustic emission activity and the ultrasonic attenuation is not possible from the results of this study, it appears that monitoring of lower level emissions, which occur while the attenuation is changing, may offer some means of relating the two phenomena. The results of this work indicate that the significant information obtained from ultrasonic attenuation and acoustic emission data pertains to different parts of the deformation and, therefore, simultaneous monitoring by both techniques constitutes a complimentary test method which yields more information about the deformation mechanisms than either technique alone.

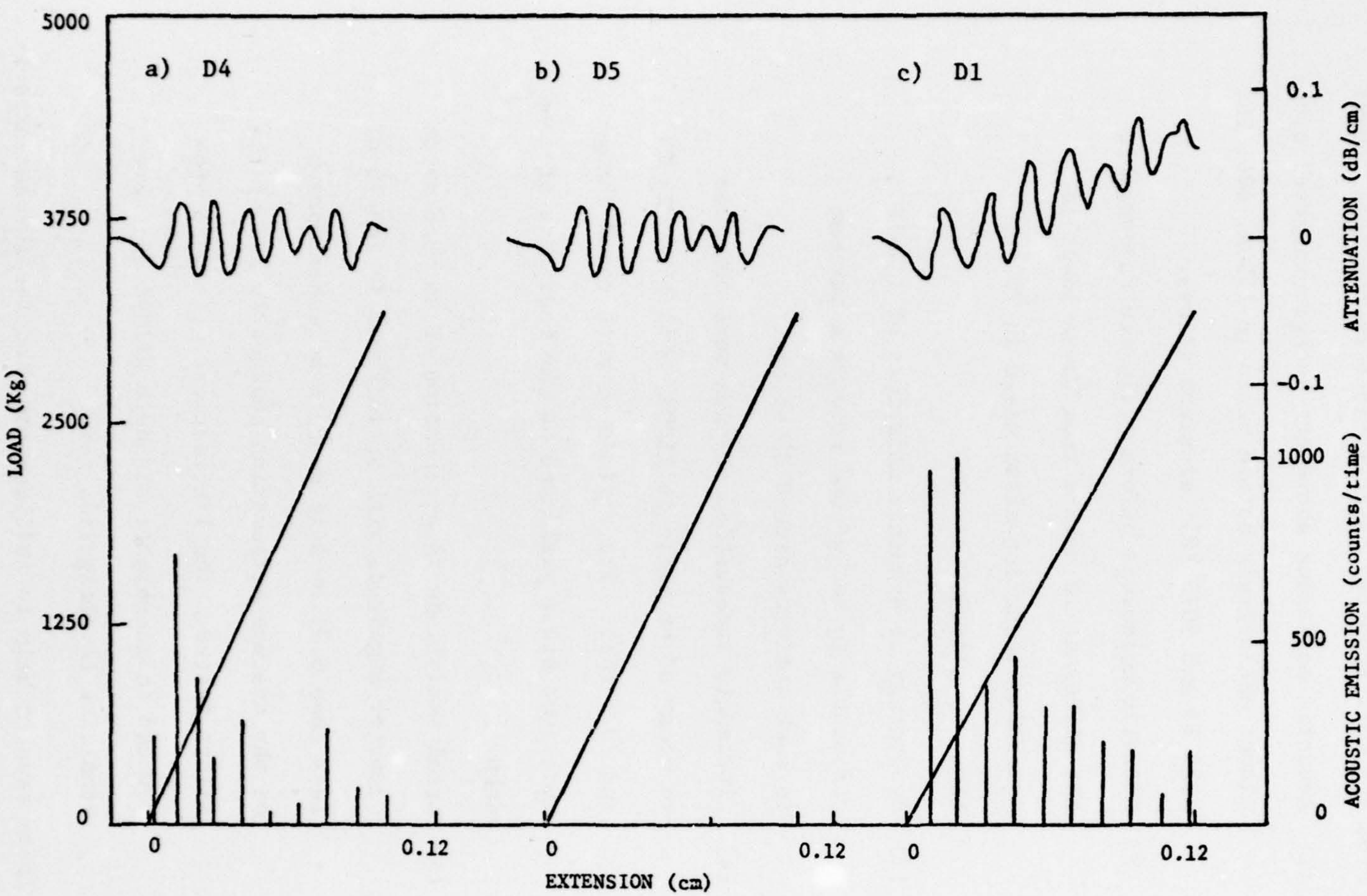

Fig. 18. Experimental Data Load-Reload Series Type 3 7075 T651 Al
Crosshead Rate 0.05 cm/min Acoustic Emission Counts/15 sec at 80 dB Gain
a) D4 Initial Loading after 80 hrs at 130°F b) D5 Reload
c) D1 Initial Loading (Reproduced)

CONCLUSIONS

From the work reported here it has been concluded that:

(1) Acoustic emissions above the background level occur almost exclusively before yield in 1100H, 6061 T6, 2024 T3 and 7075 T651 aluminum alloys.

(2) Acoustic emissions before yield are recoverable and different in nature from those lower in intensity occurring after yield in 7075 aluminum alloys.

(3) Monitoring of acoustic emissions of levels comparable to background reveals a maximum in such activity around 3% strain.

(4) Ultrasonic attenuation changes were observed to occur after yield in 1100H, 6061 T6, 2024 T3 and 7075 T651. The regions of most rapid change were just after yield and at the beginning of load drop.

(5) Local variations in attenuation of as much as an order of magnitude with an increase in length of less than 0.01 cm were seen to be superimposed on the average attenuation changes in all of the alloys tested. The fluctuations were more pronounced in the higher strength alloys and were sensitive to elongation rate.

These results help to indicate the need for further experiments in order to complete our understanding in these areas.

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VITA

John Christian Duke, Jr., was born on May 27, 1951 in Baltimore, Maryland. In 1973 he graduated from The Johns Hopkins University with general and departmental honors, receiving the degree of Bachelor of Science in Engineering. As a graduate student he has served as both a teaching and research assistant. He was chosen to receive an ASTM student award in 1975. The author is a member of the honor fraternities Tau Beta Pi and Sigma Xi, as well as a student member of ASM, AIME, ASNT and MIM.

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APPENDIX C

Summary of paper to be presented and published in the Proceedings of the Ultrasonics International 1977 Conference to be held at Brighton, England, June 1977.

Acoustic Emission: A Critical Comparison Between Theory and Experiment

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Introduction

The phenomenon of stress wave release from microstructural alterations induced in solid materials, commonly known as acoustic emission, has been the subject of an ever increasing number of scientific investigations and technological applications for the past 20 years. Nevertheless, acoustic emission monitoring has not optimally fulfilled its promise as a nondestructive testing technique since the amplitudes, frequency spectra, and propagational characteristics associated with specific defects remain unknown. The two major reasons for this state of affairs are over simplistic and unrealistic theoretical analyses and lack of careful independently verified experimental measurements.

It is the purpose of the present paper to present a detailed comprehensive review of the published theoretical treatments of acoustic emission and to critically compare each treatment with the results of experimental measurements. In addition, suggestions will be made as to how improvements can be made in both theoretical models and experimental procedures.

Theory

Figure 1(a) serves to illustrate the elementary manner in which acoustic emission is usually treated. In this commonly used portrayal, the internal source emits a spherical wave which propagates at constant speed in all directions with amplitude decreasing only because of the expanding wavefront. The surface source also emits a spherical wave with similar characteristics which radiates into the interior of the solid and in addition emits a Rayleigh wave which propagates along the surface in all directions away from the source with constant velocity and amplitude decreasing only because of the expanding wavefront.

Figure 1(b) illustrates schematically a somewhat more realistic view of acoustic emission, although even this portrayal is still over-simplified. In the case shown, the internal source emits a wave which is non-spherical initially because of the shape of the structural defect which causes the emission. After leaving the vicinity of the defect, the profile of the wavefront continues to change because of the directional variation in wave speeds associated with linear elastic wave propagation in anisotropic solids. Moreover, the amplitude of the wave decreases with increasing distance from the source, both as a result of the expanding wavefront and as a result of attenuation caused by a number of mechanisms which are active in real materials. Among these mechanisms are thermoelastic or heating effects, grain boundary scattering, acoustic diffraction, dislocation damping, interaction with ferromagnetic domain walls, and scattering by point defects.

Comparison between Figs. 1(a) and 1(b) permits a number of differences between the acoustic emission signals detected in the two cases to be discerned. A review of the mechanistic theories set forth by previous investigators compared with experimental observations casts doubt on the general validity of these theories.

<u>Experiment</u>

The most commonly used method for evaluating structural damage by acoustic emission monitoring is to count the signals emitted during mechanical deformation of the material and to plot the results as total counts or count rate as a function of some measure of the deformation such as stress, strain, or the number of fatigue cycles. A number of problems are associated with this simplistic approach including a lack of knowledge of the influence of test specimen geometry on the received signals, of the effect of the medium coupling the acoustic emission transducer to the work piece, and the amplitude and frequency response of the transducer itself. In order to make reliable assessment of such data, it is normally assumed that all events producing acoustic emissions of sufficient amplitude to be counted are equally damaging to the structure, that all damaging events will produce acoustic emissions of sufficient amplitude to be counted, and that each event will cause an acoustic emission which will be counted only once and not overlap with other signals. To make such assumptions is improper since a given high amplitude acoustic emission signal may be produced by a single event which causes damage to the

structure or by the simultaneous occurrence of a number of small events which cause no structural damage but whose net effect is to produce the large acoustic emission signal. A structurally damaging event may occur but the emissions associated with it may be too weak, propagate away from the detecting transducer, or be of the wrong frequency to be detected. A single event may take place with several emissions of sufficient amplitude that the detector records several counts for one event or a single event may be such that the direct signal and multiply reflected signals arrive at the detecting transducer at different times thus resulting again in multiple counts from a single event.

A review of the experimental literature reveals many experiments where the detection technique did not permit recording of the unaltered acoustic emission signal characteristics of the structural defect. In other experiments proper precautions were not taken to eliminate signals caused by extraneous noise sources. In most cases where the observed acoustic emission signals were assumed to be caused by a given microstructural alteration, no metallographic or other independent evidence was presented to verify the assumption. Finally, the general inapplicability of the "Kaiser Effect" is pointed out and suggestions are made as to how more reliable experimental measurements can be made.

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This research was supported in part by the United States Office of Scientific Research (AFSC). A special note of appreciation in this regard is due to Dr. Charles Hays.

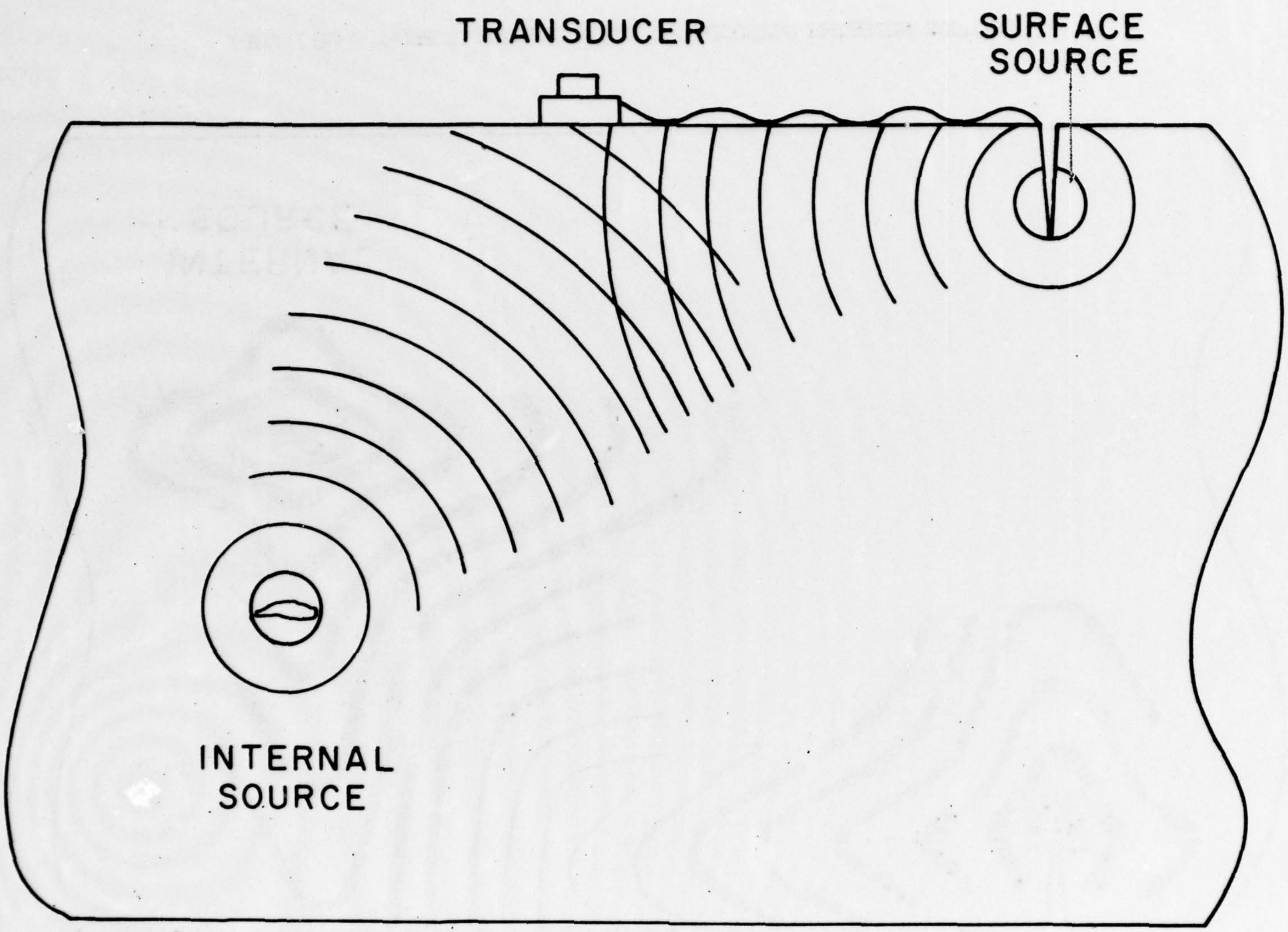

Fig. 1(a) OVERSIMPLIFIED MODEL OF ACOUSTIC EMISSION SOURCES

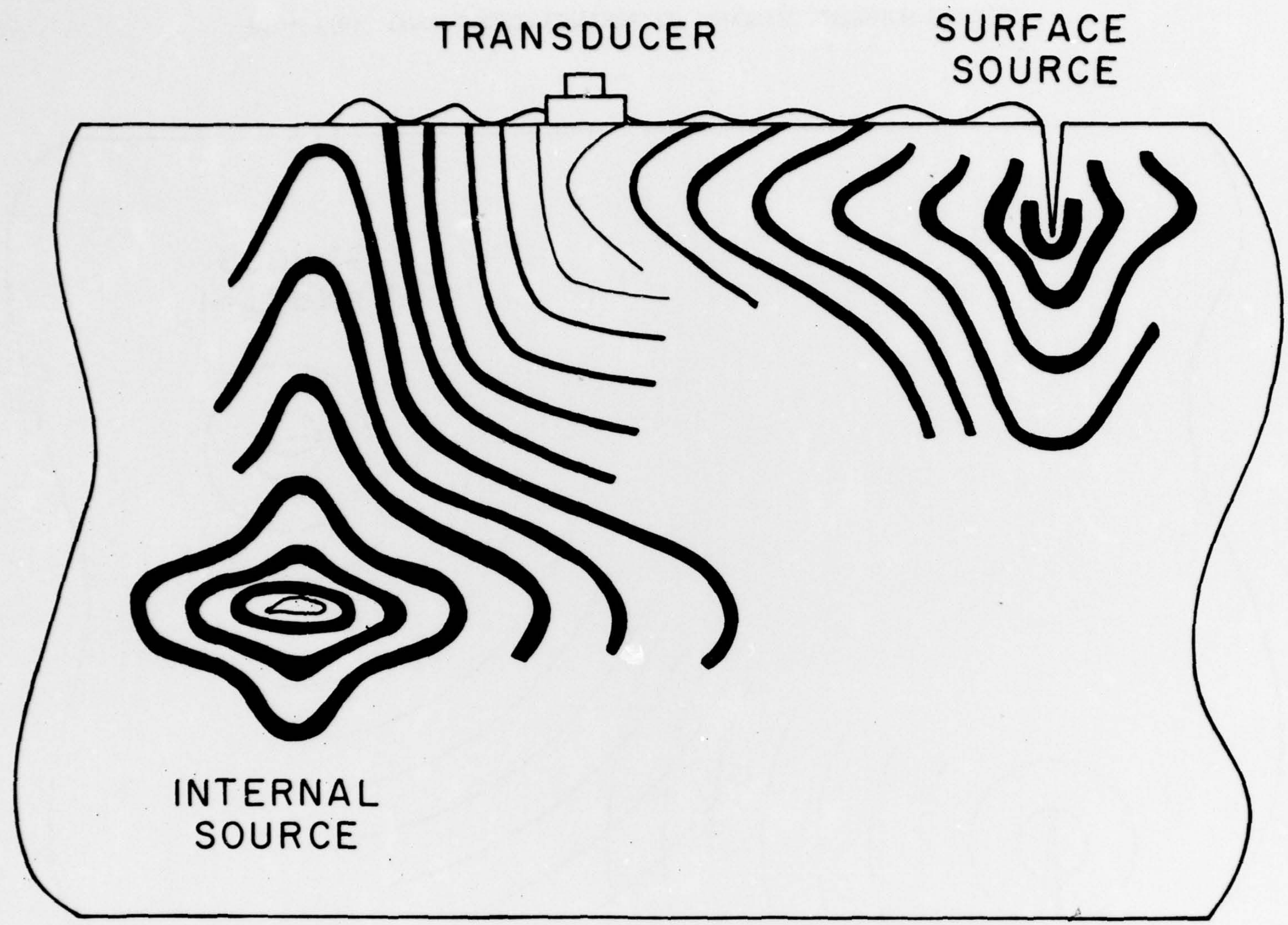

FIG. 1(b). MORE REALISTIC MODEL OF ACOUSTIC EMISSION SOURCES